Evaluating Regional Aquifer Vulnerability and BMP Performance in an Agricultural Environment Using A Multi-Scale Data Integration Approach

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The increased use of both organic and synthetic fertilizers on agricultural land has lead to rising groundwater nitrate concentrations in some areas of southern Ontario. This has occurred at the Thornton Well Field in Oxford County, likely as a result of impacts from legacy agricultural activities in the area. In an attempt to mitigate the impact on water quality within the well field, the County purchased some of the agricultural land in the vicinity of the well field in 2001 with plans to reduce nutrient loading through the implementation of Beneficial Management Practices (BMPs). Since the initiation of the BMPs, the nitrogen application rates within the study site were reduced by 20 to 100% relative to historical rates. The objectives of this study were to provide a unique, five year data set which can assist in BMP development and provide direction for regional scale agricultural policy; evaluate the nitrate mass flux at numerous locations through the unsaturated zone beneath a BMP-activated agricultural field within a complex moraine environment; develop and compare various methods to upscale point measurements of mass flux to mass loading (t $N0_3$-N/yr) at the field and regional scale; evaluate standardized methods of assessing aquifer vulnerability and compare results within the context of non-point source agricultural contaminants at the field and regional scale; and determine whether monitoring water levels and temperature within monitoring wells is able to aid in evaluating vulnerability to surface contaminants.

Information collected over two years was combined with data gathered by former researchers at the field site to create a unique and extensive data set. Nineteen new monitoring wells, including two Continuous Multilevel Tubes (CMT), were installed to further develop the geological conceptual model and identify crucial discontinuities in the aquitard units. This network was devised and installed by a team of hydrogeologists. Eight geologically and topographically diverse monitoring locations or “stations” had been previously established and monitored by Bekeris (2007) to track changes in soil nitrate mass within the unsaturated zone through successive geologic coring. This study involved the selection of seven new locations that were predicted to behave similarly to one of the original eight stations in order to assess the predictive capability of scaling up point measurements. The upscaling criteria were based primarily on near surface geology, topography and field observations, with the former being determined as exerting the greatest influence on the results. Recharge rates estimates were combined with unsaturated zone soil nitrate data obtained from geologic coring events to produce nitrate mass flux estimates. Four methods of scaling up point estimates of mass flux made at fourteen of the stations to produce mass loading estimates across the whole field site were compared. The best method displayed nitrate mass loading having

decreased within Parcel B from 6.77 t/yr in May 2006 to 2.55 t/yr in May 2008 resulting in a total mass reduction rate of 4.20 t/yr or 62 % which verifies the effectiveness of the BMPs. This corresponds well with the 46% decrease in applied nitrogen associated with the BMP. Groundwater quality measured using standard monitoring wells with long screens indicated that nitrate concentrations have ceased to increase, while groundwater taken from the discrete sampling ports of the CMT wells shows significantly lower concentrations of nitrate within the ports located closer to the water table. This further validates the success of the BMPs but suggests that there is a long lag time between BMP implementation and the flushing of deeper aquifer zones with cleaner, recharging water. Despite the decrease in applied nitrogen, crop yields have remained at or above historical values.

Three commonly applied vulnerability assessment methods including the Aquifer Vulnerability Index (AVI), Intrinsic Susceptibility Index (ISI) and Surface to Aquifer Advection Time (SAAT) were utilized to rank the vulnerability of the Thornton Well Field to surface contaminants. The results highlighted how complex hydrogeology may result in inconsistent rankings of vulnerability by each of the methods. The results from analyzing temperature and pressure data collected from pressure transducers within wells across the site suggest that these data can verify and improve the results from standardized vulnerability assessment techniques, especially during highly vulnerable snow melt events.

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Chapter 1: Introduction

1.1 Agricultural Impacts on Regional Groundwater Quality

The increased use of both organic and synthetic fertilizers on agricultural land has lead to rising groundwater nitrate concentrations in some areas of southern Ontario. There are numerous studies that name nitrate nitrogen (NO_3^--N) to be the most common pollutant that originates from agricultural practices (Spalding and Exner, 1993; Goss et al., 1998; Burkart and Stoner, 2002; Tomer and Burkart, 2003; Almasri and Kaluarachchi, 2005). It was discovered by Goss et al. (1998) in a study of farm wells in Ontario that 14 percent of these wells exceed the maximum allowable concentration (MAC) of 10 mg NO_3-N/L which was established by the Ministry of Environment (MOE). As part of the National Water Quality Assessment Program in the United States., Squillace et al. (2002) found that 11% of rural wells exceeded the U.S. Environmental Protection Agency (EPA) maximum contaminant level (MCL) of 10 mg NO_3-N/L. Nitrate contamination of drinking water is not limited to private wells. The European Environmental Agency attributes agricultural non-point source contaminants to be the principal cause of water quality degradation in many European regions (European Environment Agency, 1999). In Ontario, Canada, there have been instances of nitrate impacted municipal drinking water supply systems (Gierczak et al. (2007) and Haslauer (2005)).

It is clear that nitrate contamination of groundwater is a wide spread phenomenon. Although point sources such as manure storage tanks or waste lagoons can be a source of contamination, the groundwater quality of aquifers beneath agricultural land are typically most greatly impacted by diffuse or non-point sources. The most prominent non-point source is considered to be the land application of nitrate laden inorganic and manure fertilizers (Rudolph et al., 1998).

Consumption of nitrate-laden drinking water is associated with various types of health concerns. Nitrate toxicity is related primarily to the conversion to nitrite after ingestion. The health hazards from consuming water containing nitrate are related to the direct toxicity of nitrite. Nitrite ions (NO_2^-) can inactivate hemoglobin in the blood by oxidizing the iron moiety in hemoglobin from Fe_2^+ to Fe_3^+, or methemoglobin, hereby lowering the oxygen carrying capacity. This condition is called methemoglobinemia, or blue baby syndrome, and it is potentially fatal, usually in infants under 6 months (Wolfe and Patz, 2002). Other studies have linked nitrate in drinking water to increased risks of cancer, recurrent respiratory tract infections, hypertension and other diseases (Hill, 1999; Gupta et al., 2000; Fujiwara et al, 2000). For these reasons, maximum allowable concentrations (MAC) have been set for nitrate in groundwater. Drinking water standards are typically set at a fraction of the no observed adverse effect levels (NOAELs) since potential health risks are often unknown or hard to predict (Manassaram, 2007). In Canada, the MAC is set at 10 mg NO_3-N/L for nitrate in drinking water (Health Canada, 2006).

Nitrate can also be the root of other environmental impact. Excess nitrogen can lead to eutrophication in surface water bodies and be toxic to freshwater aquatic life if present in high enough concentrations. Nitrous oxide can be produced from nitrification or incomplete denitrification which is a greenhouse gas that depletes the ozone (Addiscott, 2004).

As a result of the health and environmental concerns relating to nitrate, agricultural nutrient management programs have been designed and employed in order to reduce the environmental impact of nitrate. Legislation in the Province of Ontario regulates the storage, handling and application of nutrients (Nutrient Management Act, 2002). Other provisions within the Nutrient Management Act include the restriction of winter application of nutrients and minimum separation distances between nutrient spreading and groundwater wells.

1.2 Aquifer Vulnerability

Aquifer vulnerability relates to how vulnerable or susceptible a groundwater resource is to contamination from either surface or subsurface sources. The overlying geologic layers are what provide the greatest protection to groundwater resources. There have been many different papers published on the topic of groundwater vulnerability spanning the past 20 years. The first such paper by Trotta (1985) investigated the use of Arc/Info GIS mapping techniques to develop a susceptibility map of groundwater to contamination across the State of Wisconsin. Groundwater susceptibility was defined by Schmidt (1987) as the ease with which contaminants can be transported from surface to the top of the water table. The work done by Trotta and Schmidt formed the basis for the development of the DRASTIC (Aller et al., 1987) approach to assessment of aquifer vulnerability. This approach often uses GIS overlay techniques to produce vulnerability maps by combining elements that can affect vulnerability such as depth to water table, geology and soil texture.

The intrinsic susceptibility of an aquifer is considered by the U.S. EPA (1987, 1997) to be associated with the overlying strata's hydrogeologic features such as stratum thickness, porosity and hydraulic conductivity. The aquifer vulnerability is considered to be a broader term that also relates to the effect of land-use practices, contaminant behaviour and loading (U.S. EPA, 1987; U.S. EPA, 1997). These early definitions are somewhat limited because they are merely qualitative and do not provide specifics as to how to quantify or compare intrinsic susceptibility and vulnerability between locations.

The U.S. EPA definitions were further developed by Focazio et al. (2002) to include in the definition of intrinsic susceptibility not only all aquifer system properties like porosity, hydraulic conductivity and hydraulic gradients as but also the related stresses on the system such as recharge, interaction with surface water, travel through the unsaturated zone and well discharge. The definition of vulnerability was modified to adopt all of the features included by intrinsic susceptibility as well as the characteristics of contaminant sources, relative location of drinking water wells and fate and transport of contaminants. While these new definitions were a definite step forward, they were still lacking protocols for quantification that could be used practically.

A practical quantification method for aquifer vulnerability was recommended by Van Stempvoort et al. (1992) which applies a vulnerability index based on the log of the advective travel time. A high index value (long travel time) signifies low vulnerability; while a low index value (short travel time) signifies high vulnerability. This method was applied for groundwater protection mapping in various parts of North America and Europe (Van Stempvoort et al., 1992). This indexing approach was enhanced by the MOE Technical Experts Committee (2004) by using physically based gradients and incorporating the unsaturated zone. This MOE method is called the surface to aquifer advection time (SAAT) approach.

These vulnerability assessment approaches are excellent ways to evaluate vulnerability in a general way. However, it can be very challenging to apply these methods in a consistent manner to specific situations like vulnerability to non-point sources in a complex, geologically diverse agricultural setting. In such settings, these approaches can produce drastically inconsistent results. The implications of using various vulnerability assessment techniques on groundwater source protection discussed in Rahman (2008) were extensively reference in this study. There remains a need to further refine these approaches or develop a protocol to determine which method to apply in particular types of settings. Furthermore, once the protocols or approaches are developed, field verification at a study site is required to substantiate the validity of the methods.

1.3 Agricultural BMPs

Under the Nutrient Management Act, beneficial management practices (BMPs) are encouraged to be adopted by farmers. These BMPs promote the use of crop rotations to reduce leaching of excess N, describe how to select and when to apply fertilizers that best meet the nutrient requirements of the desired crop, and suggest the use of cover crops during non-growing seasons to expend excess N (OMAF, 1994). The goal of the BMPs is to find a proper balance between minimizing land application of nutrients and N leaching while maintaining healthy crop growth and ensuring economic profitability (Almasri and Kaluarachchi, 2005).

For governing bodies, the goals of BMPs also includes providing sustainable drinking water supplies and groundwater quality in order to avoid the need for the construction of treatment plants or new supply wells. The European Union Water Framework Directive suggested that increasing water efficiency may be attained by setting the price of water at the full cost of obtaining clean water. Martinez and Albiac (2004) assessed various taxing systems for water and nitrogen with the goal of optimizing policy decisions for non-point source contaminants. A dynamic bio-economic model was utilized that evaluated the effects of nitrate leaching to demonstrate that taxing of emissions would produce an optimal policy. In the United States a similar approach was employed by Lee and Kim (2002) which concluded that a tax on the nitrate input is the most cost effective policy.

1.4 Need for Assessment of BMP Performance

Prior to the drafting of BMP related policies, a great deal of information pertaining to BMP performance should be collected. The interaction of many characteristics including the geology, hydrogeology and the vulnerability of groundwater to contamination should be studied. The primary difficulty in assessing the effectiveness of BMPs lies in the lag time that often exists between reduction of nutrient application at the surface and improved groundwater quality in the subsurface (Tomer and Burkart, 2003). The thickness of the unsaturated zone, the soil hydraulic properties and the variability in N application all have a great affect on the lag time. The lag times are also affected by the location of the target receptor. Whether groundwater quality is being monitored in the unsaturated zone with lysimeters, in the saturated zone with monitoring wells or at the supply well, it will increasingly lengthen the lag times due to the increasing distance to the target receptor. As a result of the long lag times, data sets spanning lengthy periods of time are often required before positive results can be considered conclusive.

Due to the long lag times, there are few studies that document the effectiveness of BMPs in reducing nitrate loading to the subsurface. A study by Meissner et al. (2002) observed a 13 year lag time between a 50% reduction of mineral fertilizer application on an agricultural field and a significant reduction in N-leaching. Wassenaar et al. (2006) concluded that a decade of voluntary BMP implementation had no effect on nitrate concentrations in the Abbotsford-Sumas aquifer that spans parts of British Columbia and Washington State. The lack of improvement may be because BMP implementation was not regulated or enforced in the Abbotsford-Sumas area and 76% of farmers operating on the aquifer did not have a nutrient management plan in place as of 2005. Another study aimed at relating improvements in groundwater quality to changes in nutrient management suggested that this process is problematic due to the impacts of past agricultural activities which result in a legacy of stored N in the unsaturated zone (McMahon el al., 2006). Tomer and Burkart (2003) detected rapid decreases in nitrate leaching within the root zone but proposed that years or even decades may pass before groundwater quality improvements are detected in the saturated zone due to long travel times from the surface. A study by Boumans et al. (1999) demonstrated that decreasing nutrient surpluses at the surface led to a decrease in nitrate concentrations in a shallow sandy aquifer beneath an agricultural area in the Netherlands.

The majority of these studies are conducted at smaller, localized settings. The integration of how factors such as the hydrogeology, vulnerability and other various field data affect BMP performance at the field scale needs to be better understood. An enhanced understanding of BMP performance at the field scale is required to help direct BMP development and improve policy making which is typically focused on a more regional scale.

1.5 Upscaling of Local Field Data

Field investigations are often limited in scope to local, small-scale areas. It can be very difficult to make predictions about physically based processes that occur distal to the locations where point measurements are taken. Having knowledge of the conditions within the capture zone of a supply well can greatly aid in making both short and long-term predictions with respect to the groundwater quality that will arrive at the supply well. With this in mind, a strategy to "upscale" local or point information to a larger field area was developed. This process involved classifying regions in the broader landscape, based on the physical setting that would be similar to conditions encountered at known locations. There are various methods by which point scale or local measurements can be extrapolated to evaluate conditions at a larger scale and there is a need to evaluate the effectiveness of these methods. The Thiessen Polygon approach is a graphical interpolation between neighbouring local measurements that permits a general weighting of the data based on relative separation between the points. This process creates polygons around each point measurement in which the value of the area within the polygon is assigned the value of the point measurement. Another common method is the Contouring method, which involves contouring point data and assigning the area between points an averaged value. The most simplistic method takes an average of all point measurements and applies it to the entire area of interest. A different method by Bekeris (2007) involves subdividing the entire area of interest into regions that are represented by the characteristics of one of the point measurement locations. These characteristics may include near surface geology, topography, potential for run-on/off, recharge and other field observations.

The highly variable nature of these characteristics and the nutrient requirements of the various crop rotations present a challenge to upscaling nitrate mass loading within agricultural fields. This challenge needs to be met with a detailed strategic protocol to determine the best method to measure and upscale nutrient mass loading in rural settings. There is a need for a protocol that will reduce the uncertainty of localized mass loading estimates so that there is an improvement in the accuracy of the mass balance and numerical modeling estimates that are required at the regional scale.

1.6 Objectives

Nitrate contamination in groundwater beneath agricultural land remains a major problem in southwestern Ontario. It is generally believed that changes in agricultural land use practices can reduce nitrogen loading to the water table. It is hypothesized that monitoring changes in the stored nitrate mass in the unsaturated zone can be used as a method to quantify the rate of decrease in stored nitrogen relative to the decrease in applied nitrogen at the surface. The objectives of this study are to:

1) Evaluate the relationship between a complex hydrogeological environment and the performance of BMPs on improving groundwater quality over time in an agricultural setting.
2) Assess whether a BMP that reduces the application of nitrogen to crops is a viable option to curb the wide spread affects of nitrate contamination of groundwater due to agricultural practices.

3) Provide a five year data set which can assist in BMP development and provide direction for regional scale agricultural policy.

4) Quantify the nitrate mass flux at numerous locations through the unsaturated zone beneath a BMP-activated agricultural field within a complex moraine environment.

5) Develop and compare various methods to upscale and extrapolate point measurements of mass flux to mass loading in metric tonnes/year (t $N0_3$-N/yr) at the field and regional scale.

6) Evaluate standardized methods of assessing aquifer vulnerability and compare results within the context of non-point source agricultural contaminants at the field and regional scale.

7) Determine whether monitoring pressure and temperature within monitoring wells is able to aid in evaluating vulnerability to surface contaminants and estimate potential lag times.

Chapter 2 provides background on the field site, previous investigations and historical land use practices. Chapter 3 describes the methods of this study with respect to the BMP investigations and the methods used to evaluate the vulnerability of the study site to surface contaminants. Chapter 4 presents field results, Chapter 5 is a discussion section and Chapter 6 contains conclusions and recommendations pertinent to the study objectives.

Chapter 2: Background

2.1 Thornton Well Field, Woodstock Ontario

The increased use of both organic and synthetic fertilizers on agricultural land has lead to rising groundwater nitrate concentrations in many parts of southwestern Ontario. Oxford County has become one of the many municipalities who now face this issue within the Thornton Well Field. This well field provides between 2 x 10^6 m^3 and 4 x 10^6 m^3 of water per year to the City of Woodstock, which represents roughly half of the city's demand. The city is located approximately 2 kilometres northeast of the well field Figure 1. Since the 1970's the nitrate concentrations within water extracted from this well field have been steadily rising. The concentrations in some wells began to exceed Ontario's MAC of 10 mg NO_3-N/L in 1994 (Figure 2). As a short-term solution, Oxford County now controls the pumping rate, alternates between supply wells and blends with water from another well field prior to distribution in order to keep the nitrate concentrations below the MAC.

2.2 Study Site Characteristics

The study site is composed of two parcels of agricultural land located north of the Thornton Well Field which are owned by the County of Oxford. Parcel B is 73 hectares in size and is bounded by Curry Road to the northwest and the well field's woodlot to the east. Parcel A is 38 hectares in size and is roughly bounded by Curry Road to the northwest, Dodge Line to the southwest and another farming property to the south east (see Figure 3).

The topography of the study site is typical of a glaciated region. It features gently rolling hills and drumlin type features, with ground elevations ranging from about 300 to 340 metres above sea level (masl) (Figure 4). Surface water within the study site drains into Cedar Creek, a tributary of the Thames River (Haslauer, 2005). The regional groundwater flow direction in the shallow supply aquifer is from southwest to northeast (Haslauer, 2005) and locally from west to east (Padusenko, 2001).

The study site is located within the Woodstock drumlin field. Drumlins are cigar-shaped land forms which are created by flowing glaciers. The longitudinal orientation of the drumlins in the area is between 280° and 330° indicating that ice flow moved in that direction (Haslauer, 2005).

The prevailing soil type at the study site is the Honeywood-Guelph complex, which is comprised of mixed silty alluvial deposits over loam till. This complex is comprised of mixed profiles including the Honeywood silt loam, soils containing a small proportion of stones, and the stonier loam-textured Guelph soils. Other soils that can be found across the site include the Fox sandy loam overlying the glaciofluvial outwash deposits described above, and the Embro silt loam which is comparable to the Honeywood series but has imperfect drainage due to its lacustrian basin origin (Wicklund and Richards, 1961).

The quaternary geology of the Woodstock area is dominated by an interlobate zone which is comprised primarily of glacial deposits. The till was formed by the deposition of sediments from several separate ice lobe movements. A small area of the study site is covered by a fine grained glaciolacustrine deposit which is found near the base of a course grained glacial outwash channel. A stony, silt till known as the Zorra Till is the most dominant sediment type found at the surface of the study site as shown on Figure 5. It was deposited by an ice lobe that came from Huron-Georgian Bay area.   Below the Zorra Till is the Catfish Creek Till and perhaps the Port Stanley Till which were deposited by an ice lobe that originated in Erie-Ontario basin (Cowan, 1975).

Due to the nature of the glacial depositional environment, the hydrogeological conditions at the study site are extremely complicated. Haslauer (2005) describes the conceptual model of the hydrogeologic system as being a 4 layered system of aquifers and aquitards with widely ranging thicknesses up to tens of metres. Aquifer 1 is discontinuous and supports a locally perched water table. It overlies aquitard 1 or aquitard 2 depending on discontinuities. Aquifer 2 is unsaturated across the site except in the east where a saturated glaciofluvial outwash channel incorporates the aquifer. Aquitards 1 and 2 are absent or discontinuous across the outwash channel. Aquifers 2, 3 and 4 are water supply aquifers with the Thornton supply wells being screened in Aquifer 3. Limestone bedrock at the site was sampled by (Haslauer, 2005) during a deep well installation at the north-west corner of Parcel B to be about 69 m below ground surface and of the Detroit River Formation. Bedrock in the region consists of dolostones and shales of Silurian age as well as Devonian limestone (Cowan, 1975). The geology of the study site is further described by Padusenko (2001), Haslauer (2005) and Bekeris (2007).

Rapid infiltration of water was indicated in some wells near the outwash channel by a marked decrease in groundwater temperature during snow melt events (Haslauer, 2005). This suggests that there was a fast connection between the surface and the water table in the outwash channel. This hydraulic connection was noted by Haslauer (2005) during a spring melt in 2004 and 2005. It is thought that aquitards 1 and 2 are absent or discontinuous within the channel (Haslauer, 2005), so it may be possible for surface contaminants to rapidly migrate to the water table.

The town of Woodstock experiences fairly uniform precipitation during the year averaging 954 mm annually. Mean monthly temperatures range from -6.3 ºC in January to 20.4 ºC in July, with an annual average of 7.5 ºC (Environment Canada, 2008).

2.3 History of BMP Implementation at Thornton Well Field

Agriculture is the principal land-use in the regions surrounding the town of Woodstock. Nutrients such as inorganic fertilizer and manure are commonly spread on the land to enhance crop yields. Agricultural activities are the biggest non-point sources of nitrate contamination of groundwater because of increased use of nitrogen fertilizer on crops and the trend toward concentrated animal farming (Burkart and Stoner, 2002). The increasing nitrate concentrations at the study site seem to correspond with the 300% increase in fertilizer that was spread in the Oxford County between 1955 and 1985 (Fertilizer Institute of Ontario Foundation, 2001). This suggests that likely the agricultural land-use in the capture zone of the municipal well field is having an impact on groundwater quality.

To curb the negative effects of agricultural practices to their drinking water supply, in 2003 the county purchased 111 hectares of land within the capture zone of the municipal supply wells. The seven fields comprising Parcel B (Figure 3) are now leased to farmers who are required to apply nutrients at reduced quantities as part of a beneficial management practice (BMP) to reduce nutrient loading to the subsurface. In exchange for agreeing to reduce nitrogen application, farmers are compensated for the value of lost crop yields due to sub-optimal nitrate fertilization. The crop type dictates the amount of nitrogen that is applied to each field. Corn is typically given starter fertilizer at planting which is followed with sidedress nitrogen in late spring. Soybeans are not fertilized because they are capable of fixing nitrogen.

Although there are no detailed records of nutrient application at the site prior to 2003, the farmer who had formerly worked the land stated that Fields 1 to 4 had rotated between grass and wheat-corn-soybean which is common in the area (Bekeris, 2007). The wheat that was being rotated was a high protein hard red winter wheat which requires high nitrogen input. In 2003, this crop was changed from hard to soft red winter wheat which requires almost 50% less nitrogen.

A livestock farm previously occupied Fields 5 to 7 (Figure 3). The manure produced on site was likely spread on these fields (Bekeris, 2007). Field 6 formerly contained a barn and pasture area where manure was concentrated which is confirmed by the high phosphorous and potassium levels that were measured in this area (Soil Research Group, 2006). Since the fields to the north of Curry road (Old Stage Road Field) are not part of the County land, they were not subject to reduction in nutrient application. In the last decade, this field has been cropped under rotation and in alfalfa which it typically grown consecutively for several years. Fields which grow alfalfa are often subject to multiple nutrient applications which can lead to excessive nitrate in the soil because no other crops are taking up the surplus nitrate.

2.4 Previous Site Studies

Elevating nitrate concentrations municipal supply wells located within the Thornton Well Field initially lead to hydrogeological investigations at the study site. There have been several previous studies completed at the Thornton Well Field. Groundwater age dating (Sebol, 2000; Sebol, 2004) and an intensive geochemical examination (Heagle, 2000) were combined with an investigation to determine the effects of agricultural practices on groundwater quality in the area (Padusenko, 2001). These studies characterized a large plume of nitrate migrating SW across the study site towards the municipal supply wells. Further site investigations by Haslauer (2005) refined the conceptual model and estimated the amount of stored nitrate in the unsaturated zone (Haslauer, 2005). Bekeris (2007) selected and installed 7 locations within Parcel B at which to monitor field parameters such as nitrate mass flux and groundwater temperature and pressure. In order estimate nitrate mass flux, soil coring of the vadose zone and various recharge estimates were completed by Bekeris (2007). These estimates were utilized by Bekeris (2007) to evaluate the effect of agricultural beneficial management practices and nutrient management schemes on groundwater quality at this site.

Many of these methods involving soil coring of the vadose zone and recharge estimate techniques developed and employed by Bekeris (2007) were utilized by this author to continue to monitor and evaluate the effects of the changes in land use practices. The heterogeneous nature of the geology at this site was established by Haslauer (2005) and Bekeris (2007). This study site has been well instrumented by Padusenko (2001), Haslauer (2005) and Bekeris (2007). The ability to use the point measurements taken at these instrumented locations to make predictions about conditions outside the current study area may prove to be extremely useful for future upscaling studies. This study will attempt to compare and utilize such upscaling techniques. This study aims to better characterize the geologic conceptual model, especially within the outwash channel where it is thought that “windows” in the aquitard connect the pumped aquifer with an overlying aquifer unit (Haslauer, 2005). These connection points may prove to be an important pathway for contaminants such as nitrate to reach the pumping supply wells. The rapid responses of groundwater temperature and pressure to snow melt events first noted by Haslauer (2005) will be analyzed and evaluated as to whether these data can aid in assessing the vulnerability of the water table to contamination.

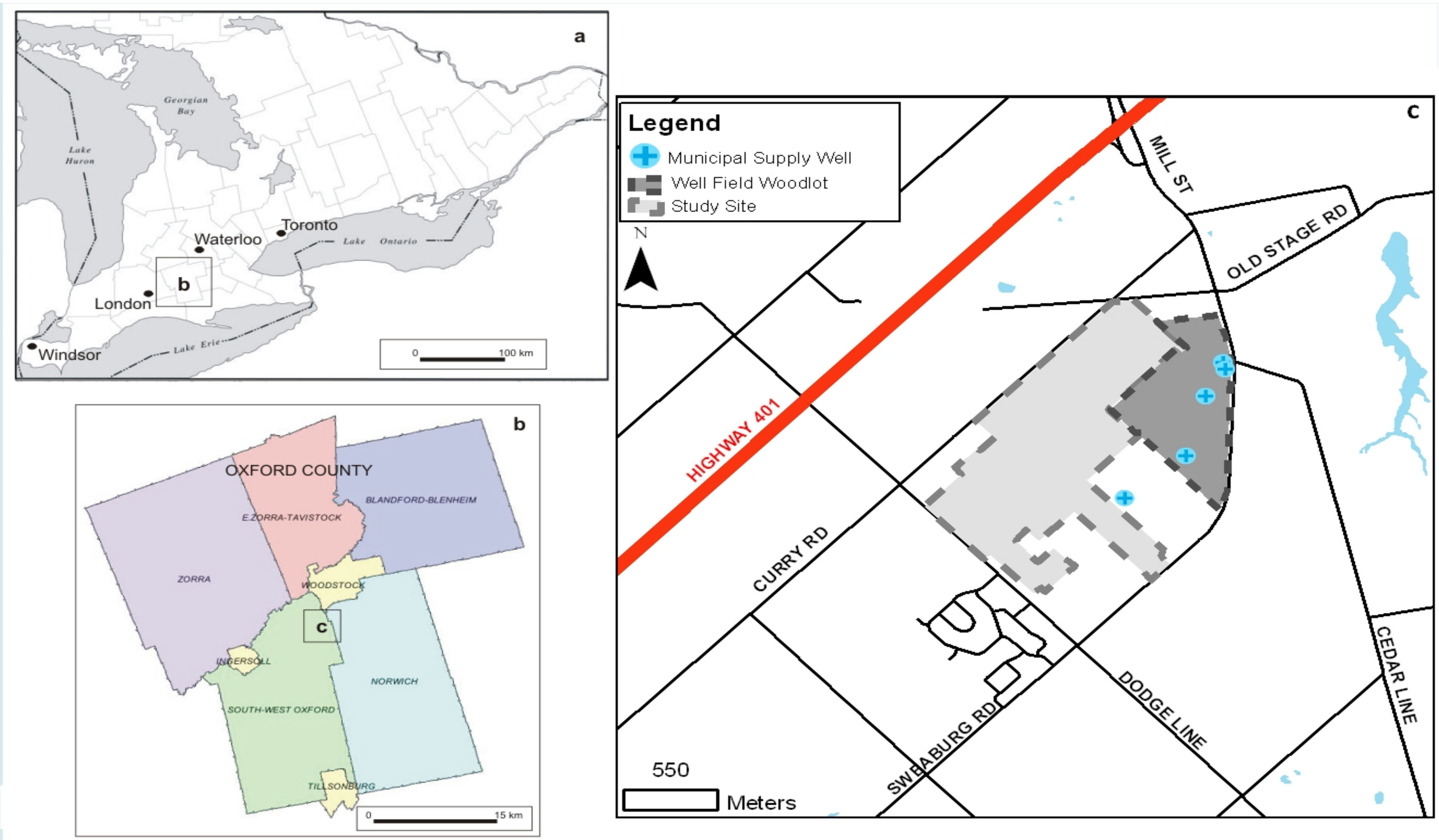


Figure 1: a) Location of Oxford County within Southern Ontario. Contains data from Brock University Map Library (n.d.). b) Location of study site within Oxford County. Contains data from The Corporation of the County of Oxford (1990). c) Study site limits, municipal well locations and surface water features. Contains data from The Corporation of the County of Oxford (1990, 2003a, 2003b, 2003c, 2003d, 2003e). Image adapted from Bekeris (2007).

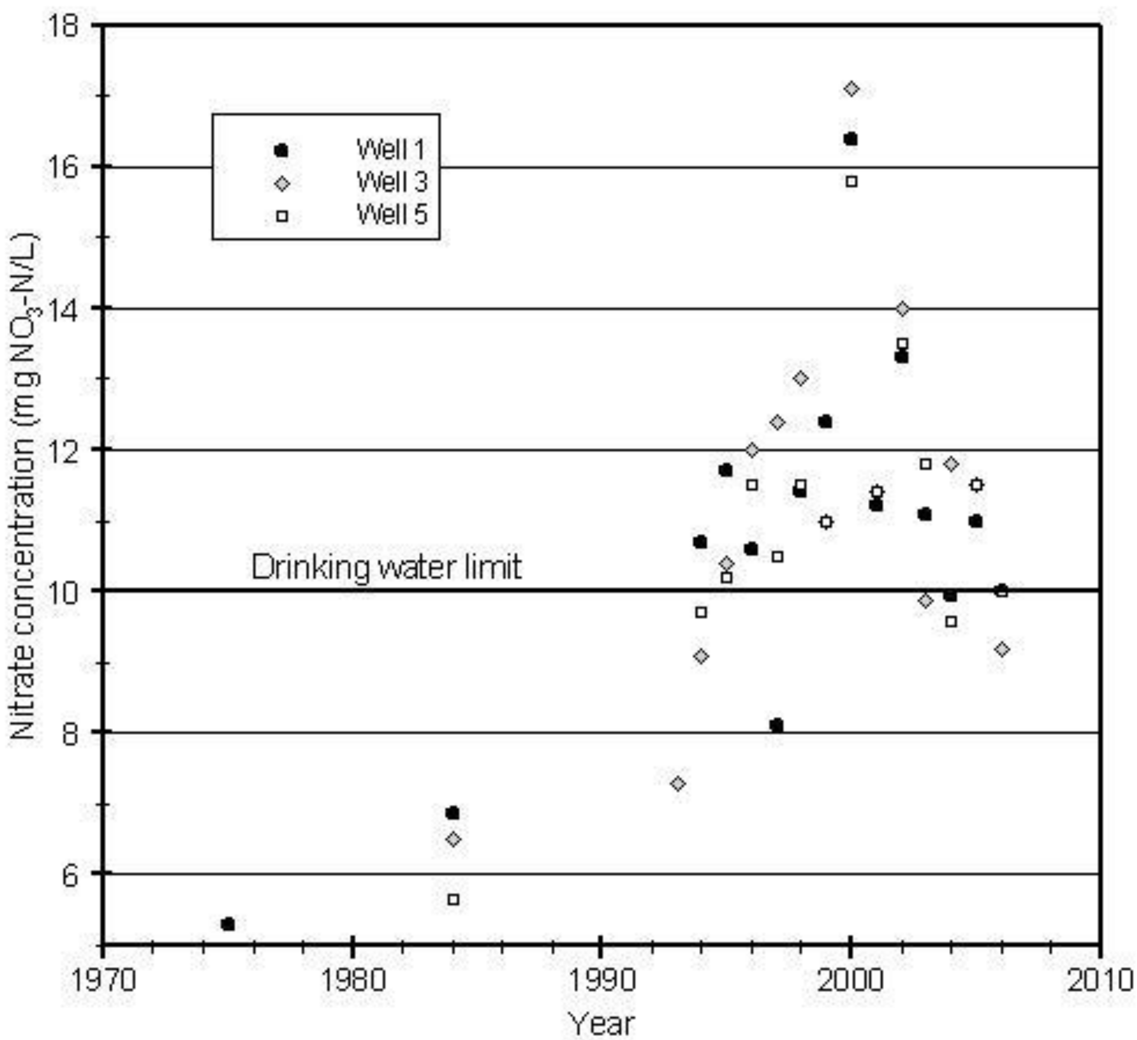


Figure 2. Historical nitrate concentrations in Thornton Well Field supply wells (from Bekeris, 2007).

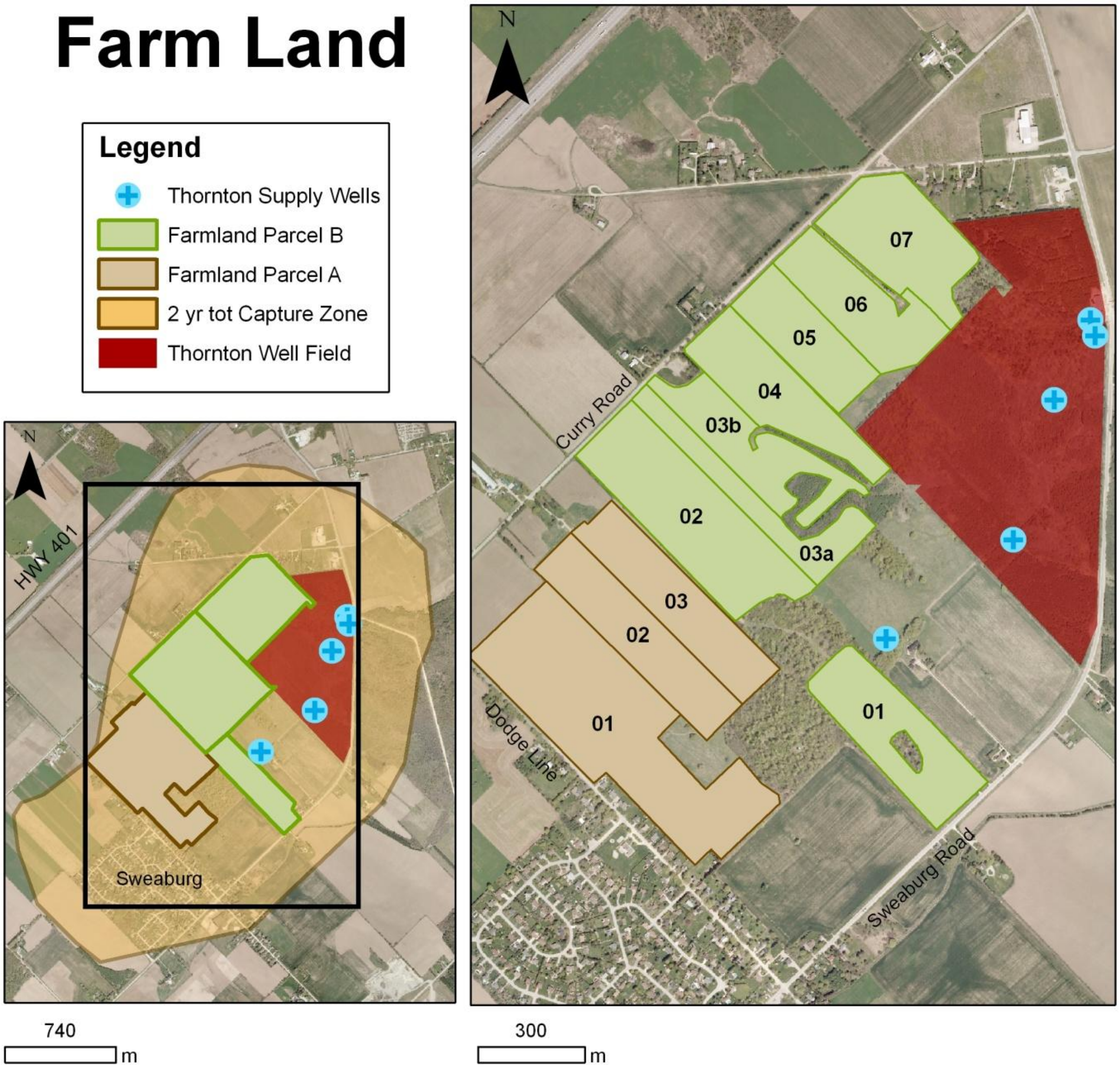


Figure 3. Farm land field number designations near the Thornton Well Field. The two year time of travel (tot) capture zones shown are from a well head protection study performed by Golder Associates Ltd (Golder Associates, 2001). (Adapted from Haslauer, 2005).

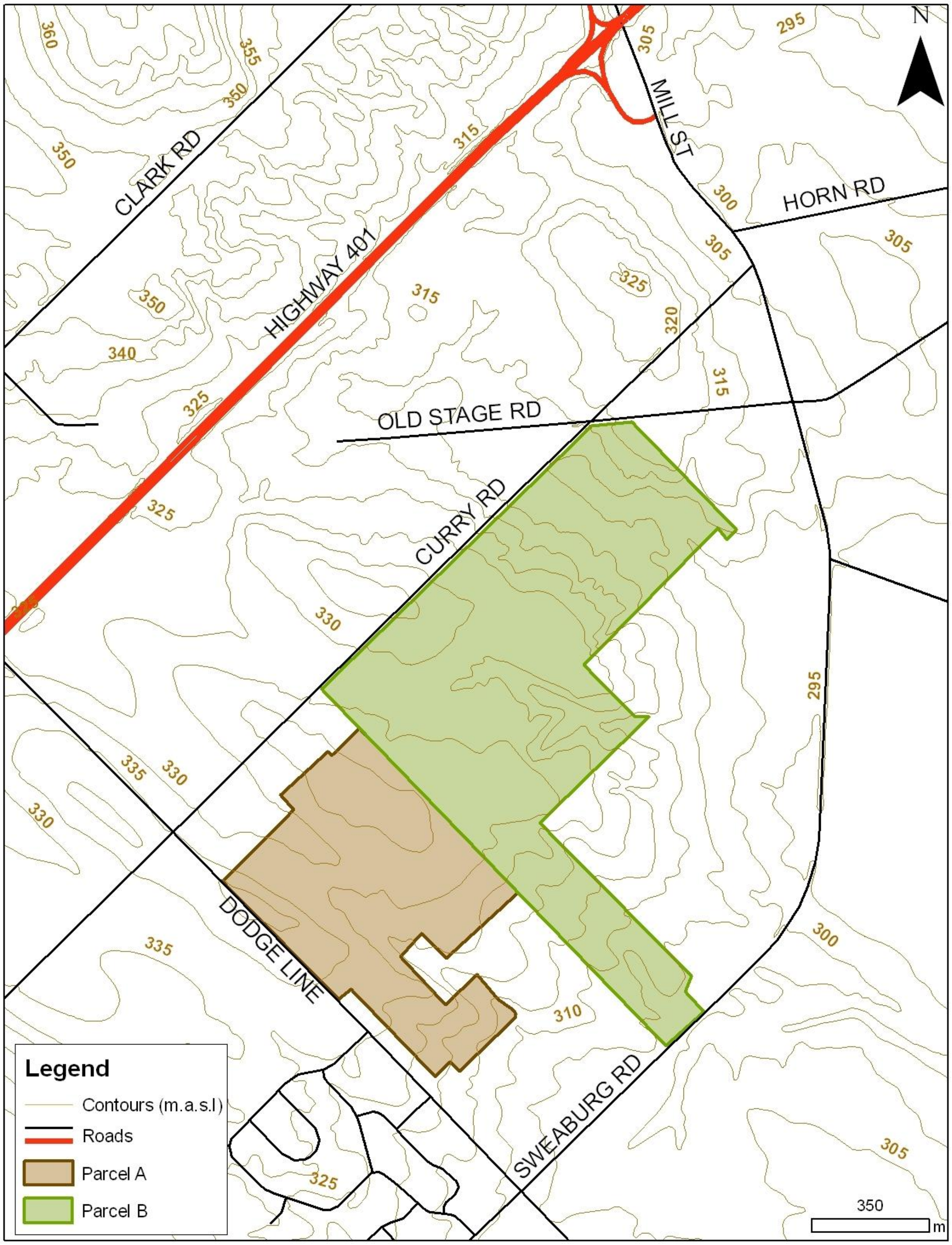


Figure 4. Land parcel subdivisions and topography of study site and surrounding area. Contains topographic data from the Corporation of the County of Oxford (1990, 2003b, 2003c).

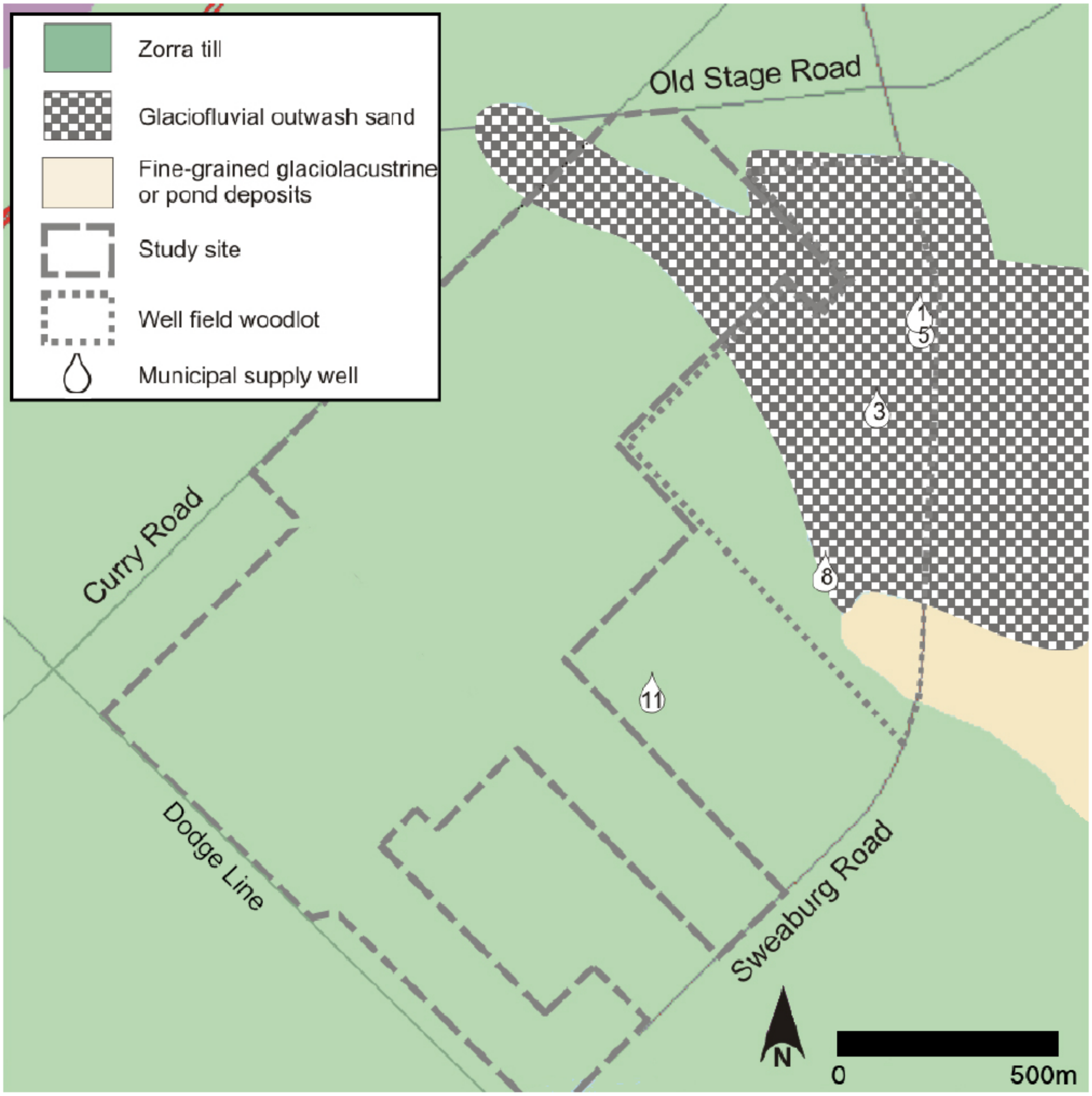


Figure 5. Surficial geology of the study site. Contains data from The Corporation of the County of Oxford (2001, 2003b, 2003c). (Adapted from Bekeris, 2007).

Chapter 3: Methods

3.1 Field Instrumentation

3.1.1 Meteorological Station

The meteorological conditions at the study site control many physical processes such as precipitation, crop growth, evapotranspiration, recharge, intensity of spring snow melt. In order to study the climatic effects on the study site, a meteorological station equipped with a Campbell Scientific Inc. (CSI) CR23X datalogger was installed on December 9, 2004 (Bekeris, 2007). It is located directly beside recharge station 2 (see Figure 6) where the topography is flat and there are no nearby trees to obstruct the instrumentation. The station features an extensive array of meteorological sensors for measurement of the following parameters: precipitation (including rainfall measurement with a tipping bucket, and snowfall measurement as rainfall equivalent using a snow adapter on the tipping bucket), relative humidity, wind speed and direction, solar radiation, soil heat flux, air temperature and barometric pressure. The meteorological station also includes five soil moisture sensors and five soil temperature sensors, which are described in detail by Bekeris (2007). The datalogger was programmed to collect and record data every 15 or 60 minutes for each sensor. The data is sent via a telemetry system to a computer in a laboratory at the University of Waterloo.

3.1.2 Neutron Probe Access Tubes

In order to estimate recharge and porewater concentration across the study site, it was necessary to take soil water content measurements. Prior to the onset of this study, each of the original eight recharge stations were equipped by Bekeris (2007) with a 5.1 cm (2-in) outside diameter access tube. During this study, access tubes were installed at stations 9-11 and 12-15 on November 21, 2007 and December 4, 2007 respectively (Figure 7). A Vibra-Push® direct push rig equipped with the Enviro-Core® sampling system was utilized to advance a 5.1 cm (2”) diameter core barrel to collect a continuous geologic core in polyurethane tubes. In order to prevent moisture loss, the 0.91 m (3-ft) long core tubes were capped and sealed in the field and refrigerated at the University of Waterloo until analysis for physical and chemical properties were performed. A 5.1 cm (2”) outside diameter, Schedule 40, PVC riser pipe with a threaded bottom cap was installed snugly into the borehole. The average depth of the PVC access tubes was about 5.3 metres below ground surface (mbgs). The locations and names of access tubes 1 through 26 are shown on Figure 7.

3.1.3 Monitoring Wells

Prior to this study, an extensive network of monitoring wells (WO02 to WO66) had been installed throughout Parcel B, especially in Field 7. However, there were many areas that had not yet been adequately characterized with respect to the hydrogeology. For this reason, an extensive well installation campaign was set forth. Seventeen monitoring wells and 2 Continuous Multilevel Tubing (CMT) installations were completed between November 14, 2006 and January 17, 2007 at 10 locations by Boart Longyear using a Rotosonic mini-sonic drill rig (Boart Longyear Inc., North Bay, Ontario). Drilling and installation of wells WO67 to WO76 were overseen by University of Waterloo personnel. The wells were installed from 6.1 to 42.7 mbgs and constructed using 2" inside diameter schedule 40 PVC casing and either a 1.51 or a 3.02 m (5ft or 10 ft) long well screen. Furth details are described in Section 4.1.

The Rotosonic drilling method supplied continuous soil cores that were subsequently returned to the University of Waterloo where the materials were classified using the Unified Soil Classification system. About 500 m of soil core was logged. A geologic and well construction log was created for each well using LogPlot 2005 (Rockware Inc., Golden Colorado).

Following installation, each well was developed using a submersible or peristaltic pump and collected between January 10 and February 22, 2007. Hydraulic tests (i.e., slug tests) were performed on 16 of the 17 new wells to determine the hydraulic conductivity of the materials near the well screen (WO72-S was unable to be tested because of a damaged casing). Between 7 and 12 tests (both falling and rising head tests) were performed on each well using Model 3001 Levelogger LT pressure transducers (Solinst Canada Ltd., Georgetown Ontario) to monitor water level changes.

3.1.4 Recharge Stations

In order to assess the spatial variability of groundwater recharge and nitrate mass load, it was necessary to gather data at various locations across the study site. For this reason, eight study locations ("recharge stations") were selected by Bekeris (2007) to represent a range of topographic and geologic conditions found across the study site. Boreholes drilled previously by Haslauer (2005) that were located at or proximal to the stations formed the basis of the initial geologic assessment of the stations. Many of these boreholes did not reach the water table and therefore represented the shallow stratigraphy (3 to 10 m). Recharge station locations were not sited by Bekeris (2007) in Fields 1 and 2 (Figure 3) because these fields were beyond the scope of the initial study. In order to collect more data and to test upscaling predictions (see Section 3.7), seven new recharge stations were selected and instrumented in December 2007. Several of the new stations were located in the Parcel A area. The locations of all 15 recharge stations with their associated monitoring wells are shown on Figure 8.

For a detailed account of the equipment installed at the original eight stations, see Bekeris (2007). Each of stations 9-15 which were installed during this study were equipped with a neutron probe access tube as described in Section 3.1.2. Stations 9, 12 and 13 are located within 4 metres of an existing monitoring well (Figure 8).

3.1.4.1 Field Equipment Burial

The recharge stations were established in actively farmed fields in order to obtain field data that were most representative of groundwater recharge and nitrate mass load below active agricultural land. Whenever possible, field equipment was buried below farming implement penetration depths during times of planting and harvesting to allow normal agricultural activities to occur at the recharge stations.

3.2 Bromide Application

In order to quantify vertical solute transport in the unsaturated zone and directly measure groundwater recharge rates, a sodium bromide (NaBr) conservative tracer was applied at ground surface at recharge stations 1-4, 6, and 9-15 between January 8 and 9, 2008. An application area measuring 3 by 3m (9 m^2) was established at each station, and was designed to overlap or be immediately adjacent to the neutron access tubes. A solution of 5.5 kg NaBr dissolved into 18 L of deionized water was applied evenly across the application area in 2.25 m^2 increments using a watering can. This application was equivalent to an aqueous concentration of 237 g Br/L in the tracer solution, or an applied surface concentration of 0.47 kg Br/m^2. Although some of the fields had winter wheat planted or the remnants from corn harvesting on the fields at the time of tracer application, efforts were made to ensure consistent tracer application to the soil surface. Cores were later taken on May 5-7 2008 at each NaBr tracer locations in order to track the movement of the Br pulse through the subsurface. These cores were collected within 2 m of the original cores taken for the neutron probe installations.

3.3 Field Data Collection

3.3.1 Neutron Moisture Probe

Soil moisture profiles were recorded periodically at each of the recharge stations during the course of the study. The method used to collect soil moisture content values using a Neutron Moisture Probe is described as follows. A Model 503 DR Hydroprobe Neutron Moisture Probe (CPN International Inc.) was utilized as a part of this study to measure soil water content at each of the recharge stations. The probe uses 50 mCi Americium-241/Beryllium as a source of fast neutrons. The device measures the proportion of fast neutrons emitted from the probe that are reflected back as slow neutrons after colliding with hydrogen atoms in water molecule within the soil. The moisture content is determined from the neutron probe count ratio (CR); defined as the raw neutron count divided by the neutron count in a standard medium. By applying a linear calibration equation, the CR can be converted into moisture content (Bekeris, 2007).

The neutron moisture probe was lowered down the inside of access tubes, stopping every 0.15 m to take measurements in order to collect CRs. The CR was determined based on neutron emission and reflection over a 16-second time interval at each of these measurement depths. Prior to the start of this study, Bekeris (2007) collected neutron probe measurements at each of the original eight recharge stations on average bi-weekly from March 1 to December 31, 2005. In 2006, the approximate measurement frequency decreased to once per month for this study, although several measurements were taken in March 2006 during the spring melt. For this study, measurements were taken at all 15 recharge stations throughout 2007 and 2008 approximately monthly.

The model 503 DR Hydroprobe is supplied with a factory suggested calibration equation for measurements taken in 5.1 cm (2-in) PVC wells. Literature suggests, however, that site- and soil-specific calibrations are necessary for reliable measurements (Greacen et al., 1981; Yao et al., 2004). Additionally, no factory suggested calibration equation was supplied for the 8.9 cm (3.5-in) PVC access tubes installed by Bekeris (2007). Therefore a field calibration program was conducted by Bekeris (2007) at the study site in November 2005 and the results of that work were utilized in this study. The work by Bekeris (2007) was based on comparing probe measurements in several 5.1 cm and 8.9 cm access tubes with the gravimetric moisture content of the corresponding core that was collected during installation. For details and results of this calibration, see Bekeris (2007).

3.3.2 Geologic Cores

During installations for monitoring wells WO67 to WO76 in November 2006 to January 2007 (see Section 3.1.3), and during the neutron access tube installations in November to December 2007, geologic cores were collected. Cores for soil water chemistry analysis were also collected in May 2007 and May 2008 using a Vibra-Push® direct push rig equipped with an Enviro-Core® sampling system. This rig utilized a 5-cm (2-in) diameter borehole to collect continuous geologic core. Prior to this study, cores were also collected at various locations throughout the study site which are described by Bekeris (2007). Core collection provided valuable information with respect to stratigraphy, soil nitrate and bromide concentration as well as soil moisture content. The cores collected in May 2008 from the bromide application areas were obtained approximately 4 months after tracer application and so provided insight into the vertical transport of the bromide tracer. The average depth of the continuous core samples in May 2008 was 4.9 m. These samples were collected from near the centre of the 3m by 3m bromide application area at recharge stations 1-6 and 9-15, using the Enviro-Core® sampling system. The 5.1 cm (2-in) diameter, 0.9 m (3-ft) long geologic core tubes collected at each subsequent depth interval were sealed in the field and analyzed at the University of Waterloo as described in Section 3.3.6. All boreholes were immediately backfilled with bentonite chips to 10 cm (4-in) below ground surface.

Comprehensive stratigraphic logging using the United Soil Classification System (ASTM, 2006) was performed on all cores. Where geologic core was missing and the exact depth of the interface between successive geologic layers was unknown, drilling notes and sudden changes with depth in the moisture content profile were used to estimate the interface depth. The stratigraphic record obtained from cores taken by Bekeris (2007) are found on Figure 9.

3.3.3 Groundwater Level and Temperature Monitoring

A Levelogger pressure transducer equipped with a temperature sensor (3001 Mini LT, Solinst Canada Ltd., Georgetown Ontario) was securely hung in the monitoring well at recharge stations 1-8 in June 2005 and programmed to record water level and water temperature hourly (Bekeris, 2007). These pressure transducers were periodically removed for downloading and occasionally for repair or were replaced by Levelogger Gold Model 3001 LT pressure transducers in December 2005 (Bekeris, 2007). Each of the monitoring wells that were installed in the November 2006 to January 2007 coring campaign had Levelogger Gold Model 3001 LT pressure transducers installed shortly after their commissioning along with direct read cables. A barometric pressure transducer was utilized at the site to subtract the atmospheric pressure from the total pressure measured in each of the wells by the leveloggers to calculate the groundwater level in each well. Groundwater levels in these wells were also periodically measured manually throughout the study period in order to confirm and calibrate the electronic measurements. On May 21 and 22, 2008, the water levels for the majority of the wells in the network were measured.

3.3.4 Water Sampling

In order to determine the groundwater nitrate concentration at each well screen and to monitor regional groundwater nitrate trends, groundwater samples were collected from the monitoring well network. Eleven wells were sampled on October 2 and 5, 2007 and 38 wells were sampled between October 30 and 31, 2007. On May 21 and 22, 2008, 44 water samples were collected. Well sampling protocols varied from well to well depending on well diameter, hydraulic conductivity of the material surrounding the well screen and the depth to the well. Typically, the well sampling protocols were as follows. The static water level in each well was measured followed by the calculation and purging of three well volumes of water. Groundwater samples were then pumped into 500 mL bottles. Most wells in which the static water level was within 8 metres of ground surface were purged and sampled with a Geopump Series II peristaltic pump (Geotech Environmental Equipment Inc., Denver, Colorado) with 0.32 cm (¼”) outside diameter high density polyethylene (HDPE) tubing. HDPE tubing was used for each well and for wells with known nitrate concentrations (from previous sampling rounds), wells were sampled in order from lowest to highest nitrate concentration. The tubing was decontaminated between each sample location by rinsing with deionized water followed by pumping out the three well volumes of purge water prior to sampling . Deeper wells where the water level was beyond the suction limit of the peristaltic pump (~9.8 m) were purged and sampled using dedicated Waterra tubing (Waterra Pumps Ltd., Mississauga, Ontario) with a foot valve or a Grundfos Rediflow 2 submersible pump (Grundfos Canada Inc., Oakville, Ontario). All water samples were stored in ice-packed coolers and kept out of direct sunlight in the field. The samples were then transported to the University of Waterloo laboratory where they were refrigerated until analyzed for nitrate and select samples for chloride and bromide using a Dionex ICS 3000 ion chromatograph (Dionex Corp., Bannockburn, Illinois) equipped with a Dionex Ionpac AS 4 x 250 mm analytical column and a KOH eluent. Replicate field and lab samples were collected and analyzed to ensure consistent results. The nitrate concentrations that were measured as a result of these sampling events were contoured using the Surfer 8© version 8.05 contouring program (Golden Software Inc., 2004).

3.3.5 Isotopic Analysis

Natural, stable isotopes can prove to be a very useful tool to determine the source of nitrate in groundwater. Twenty wells in and around Parcel B were chosen for water sampling based on factors such as previously known nitrate concentrations, elevation, stratigraphy at well screen, proximity to production wells and proximity to previous land use practices. The samples were stored in 500 mL bottles and kept at approximately 4 °C until submitted to the Environmental Isotope laboratory at the University of Waterloo to determine concentrations of ^{15}N and ^{18}O. When the two isotopes for a particular sample are plotted against each other, the source of the water can be inferred (see Figure 10). For example nitrate that originated as manure (animal waste) will show an enriched ^{15}N value with a depleted ^{18}O value whereas water that has been in contact with a nitrate fertilizer will be enriched in ^{18}O but be depleted in ^{15}N (Bleifuss, 1998).

3.3.6 Geologic Core Analysis

Three different sets of cores were collected during the course of this project. The first set of cores was collected on May 7-9, 2007 at each of the eight existing recharge stations. The second set consisting of 7 cores was collected in November and December 2007 as part of the establishment of the seven new recharge stations. The third set of cores were collected on May 5-7, 2008 and consisted of 13 cores collected at each of the recharge stations (except for stations 5 and 7) plus one in the field west of station 8. Prior to this study, sets of cores were collected at stations 1 to 8 in February, March and November 2005 as well as in May 2006 as described by Bekeris (2007). All cores collected were analyzed for moisture content and nitrate. The soil from the first and third coring events was also analyzed for bromide. The soil analysis protocols are explained below.

The cores were stored in either a laboratory refrigerator or freezer until analysis could be performed. Each core was opened and the soil was immediately sampled for moisture content analysis at sample length intervals ranging from 0.04 to 0.15 m, with typical distances between samples of 0.15 m increasing if stone content or recovery impeded sample taking. The soil sample was extracted from the core, weighed, oven-dried at 110°C for 24 hours and reweighed (ASTM, 2005). The mass of the soil samples ranged from 15 to 125 g, depending on grain size and packing within the core. Gravimetric moisture content (θ_g) (M/M) was calculated from:

$$\theta_g = \frac{W_w}{W_s} \tag{1.1}$$

where W_w (M) is the mass of water in the soil sample, and W_s (M) is the mass of the solid particles in the soil sample. Volumetric moisture content (θ_v) (V/V) was determined based on sample volume:

$$\theta_v = \frac{V_w}{V_s} = \frac{\left(\dfrac{W_w}{\rho_w}\right)}{A_{core} \cdot l_s} \tag{1.2}$$

where V_s (V) is the volume of the sample, V_w (V) is the volume of the water in the sample, ρ_w (M/V) is the density of water, assumed to be 1 g/cm^3, A_{core} (L^2) is the cross-sectional area of the core tube, and l_s (L) is the length of the soil sample. Soil bulk density (ρ_b) (M/V) was also calculated for soil samples as:

$$\rho_b = \frac{W_s}{V_s} \tag{1.3}$$

Occasionally when opening core tubes containing loose, coarse-grained material, some material would fall out of the tube. For these samples, θ_v and ρ_b could not be determined because the exact sample volume was unknown.

Soil nitrate and bromide analysis of samples was performed at the University of Waterloo. For this analysis, five g of dry soil was added to 50 ml of deionized water and shaken for 18 hours, and subsequently allowed to settle or be centrifuged. The extract solution was analyzed using a Dionex ICS 3000 ion chromatograph equipped with a Dionex Ionpac AS 4 x 250 mm analytical column and a KOH eluent. The Dionex ion chromatograph is calibrated to be accurate to 0.1 mg/L for core samples and 0.5 mg/L for groundwater samples.

Aqueous nitrate and bromide concentrations (C_{aq}) (M/V) in the porewater of each sample were calculated from the bulk soil concentration (C_{soil}) (M/M), the gravimetric water content and an assumed water density of 1 g/cm^3. Assuming no sorption of the ions to the soil matrix and that the density of the water sample containing the nitrate can be approximated by the density of water (1 g/cm^3), this is calculated by:

$$C_{aq} = \frac{C_{soil}}{\theta_g} \rho_w \tag{1.4}$$

3.3.7 Cumulative Stored Mass Estimates

A detailed analysis of all geologic logs, gravimetric moisture content and neutron moisture probe measurements was conducted for each of the 15 recharge stations and a cumulative stored nitrate mass profile was completed along each core. In order to reduce the effect of the root zone and seasonal nitrate fluctuations, the top 1.0 m of the subsurface was excluded from calculations related to nitrate concentration and stored mass. This was done because a crop growing at the core location may have removed a significant amount of the nitrogen before it leached downward beyond the root zone. Also, in the shallow subsurface, the fate of nitrogen may be subject to a range of simultaneous transformation processes due to the nitrogen cycle such as mineralization, nitrification and denitrification. The cumulative stored mass $M_{cum,j}$ (M) at given point *j* in the profile starting at a depth of 1.0 m was defined as:

$$M_{cum,j} = \sum_{i=1}^{j} \left[C_{soil,i} \cdot d_i \cdot \rho_{b,ave} \right] \tag{1.5}$$

where $C_{soil.i}$ and d_i (L) are the soil concentration of a soil sample and the depth interval represented by the sample; $\rho_{b,ave}$ is the average bulk soil density of samples from across the site; and 1 through *j* are sampling points between 1.0 m depth and the point *j*.

3.3.8 Porewater Concentration Calculations

The average porewater nitrate concentration in the core was determined using a weighted average soil nitrate concentration and the average gravimetric soil water content. A unit area of 1 m^2 was used to simplify the calculation. As described in Section 3.3.6, geologic cores were sampled at 0.04 to 0.15 m intervals and submitted for nitrate analysis. The depth-weighted average soil nitrate concentration from a core was estimated from:

$$C_{soil,ave} = \frac{\sum_{i-1}^{j} C_{soil,i} \cdot l_i}{\sum_{i-1}^{j} l_i} \tag{1.6}$$

where $C_{soil,i}$ is the soil nitrate concentration in a geologic core sample, l_i (L) is the vertical core interval corresponding to the $C_{soil,i}$ sample, and 1 through n represent core samples.

The average gravimetric water content ($\theta_{g,ave}$) (M/M) was ascertained by averaging the individual sample's gravimetric water content's concentration over the length of the core below 1 mbgs. Lastly, the average porewater nitrate concentration $C_{aq,ave}$ is expressed by:

$$C_{aq,ave} = \frac{C_{soil,ave}}{\theta_{g,ave}} \rho_w \tag{1.7}$$

3.4 Recharge Estimation

3.4.1 Tracer Velocity Method

The tracer-based recharge rate (R_{tracer})was approximated as the product of the tracer's vertical velocity (v) and the average volumetric water content ($\theta_{v,ave}$) in the zone of migration, as represented by:

$$R_{tracer} = v\theta_{v,ave} = \frac{\Delta z_{tr}}{\Delta t} \theta_{v,ave} \tag{1.8}$$

where Δz_{tr} represent the distance traveled by the centre of mass of a tracer applied at ground surface, and Δt represents the time of travel (Scanlon et al., 2002). The tracer used was bromide which was applied to the surface as NaBr dissolved in deionized water in January 2008 (see Section 3.2). The tracer velocity is calculated from the depth of the tracer's pulse centre of mass and the time elapsed since application. Recharge using this method could only be estimated over the time period from application in January 2008 to geologic coring in May 2008. Bromide is considered an ideal tracer because it is conservative. The bromide tracer pulse centre of mass for a given sampling event was calculated from:

$$z_{centre} = \frac{\sum_{i=1}^{n} C_{soil,i} l_i z_i}{\sum_{i=1}^{n} C_{soil,i} l_i} \tag{1.9}$$

where $C_{soil,i}$ is the bulk soil bromide concentration (mg Br/kg soil) of a geologic core sample, l_i is the length of core represented by $C_{soil,i}$, z_i is the midpoint depth of the core sample and n is the number of samples within a profile. The value of $\theta_{v,ave}$ within the zone of migration was determined from neutron probe data collected during the period of tracer migration. For movement in the upper 0.3 m of the soil profile where neutron probe measurements are unreliable due to neutron losses to the atmosphere, laboratory-measured volumetric water content values from the geologic cores were used to calculate $\theta_{v,ave}$.

In order to ascertain how much bromide is beneath the test area, a mass balance of the bromide tracer was completed by expanding the bromide concentration profile of the geologic core to the entire tracer application area. The total bromide mass M_{Br} (M) at a recharge station during a given coring event was calculated from:

$$M_{Br} = \left(\sum_{i=1}^{n} C_{soil,i} l_i \right) \rho_{b,ave} A_{Br} \tag{1.10}$$

where $\rho_{b,ave}$ (M/V) is the average soil bulk density of samples across the study site (3.3.6) and A_{Br} is the area of the bromide tracer application. This approach assumes a uniform bromide distribution below the tracer application area and no horizontal transport of the tracer beyond the application area.

3.4.2 Water Balance Method

An elementary water balance equates water inputs such as precipitation, irrigation and run-on to water outputs like evapotranspiration (ET) and run-off to determine infiltration or recharge. The measurement of precipitation and the approximation of ET using empirical methods allow the estimation of surplus water (i.e., the total of run-off and recharge) at a location.

3.4.2.1 Evapotranspiration Calculation

This study estimated ET using a method described by the Food and Agriculture Organization of the United Nations (Allen et al., 1998) which was further refined by Bekeris (2007) for environments characteristic of southern Ontario. This modified method which was applied to Fields 2-7 for 2005-2006 by Bekeris (2007) and was applied in this study to these same fields as well as to Field 1 and to Parcel A for 2007 and 2008. A daily reference ET value (ET_o), corresponding to the anticipated potential ET for a standard grass crop under optimal agronomic conditions, was calculated using numerous climatic parameters measured on-site at the meteorological station. The ability of this method is limited because the estimation of potential ET value during conditions where the soil is frozen or snow covered violates the assumption of a sustained grass reference crop (Allen et al., 1998). As suggested by Allen et al. (1998) for these conditions, an average ET value of 1 mm/day was used. In this study, these conditions were assumed to correspond to the period in which average air temperatures were below zero degrees Celsius. Some of the parameters measured at the MET station that were incorporated into the ET calculation include air temperature, atmospheric pressure, relative humidity, solar radiation and wind speed. In order to estimate the actual ET from the fields under their specific crops and growing conditions, calculations were performed to estimate the daily adjusted ET values for each of the crop types grown across the study site from January 1, 2007 to October 31, 2008. This calculation incorporated many meteorological factors as well as land-use data obtained from farming records, crop growth data, precipitation and the potential development of soil water stress conditions. Sample calculations can be found in Appendix A but for more procedural details, see Bekeris (2007).

Meteorological data from the onsite meteorological station was used for all calculations except for November and December 2008 which at the time of calculation had not yet been recorded. In order to estimate precipitation and ET values for November and December 2008, the historical precipitation data from 1971-2000 (Environment Canada, 2008), the precipitation data collected at the meteorological station from 2005-2007 and the corresponding ET water balance calculations were analyzed. The values used were approximately equal to the average of the 2005-2007 water balance values for both precipitation and ET.

3.4.2.2 Recharge Calculation using Water Balance

The other main water balance components observed at the recharge stations are precipitation and recharge. Run-off was infrequently observed and only during times when sudden, short-lived above zero temperatures lead to snow melt periods during the winter and early spring. These times corresponded to the period in which ET_o values were set to 1 mm/day. The water balance for each station was completed by subtracting the adjusted ET value from the measured precipitation (P), where each term is the sum of daily values during the study period. The result represents the surplus water available at each station for either run-off or recharge. Because the magnitude of run-off is unknown, the surplus water value represents an upper bound on the potential recharge at each recharge station as expressed by:

$$R_{water\,balance} < Surplus\,water = P - ET \tag{1.11}$$

3.4.2.3 Recharge Calculation using NaBr Tracer

The recharge rate obtained from the approximate 119 days between bromide tracer application (January 8-9) and coring (May 5-7) were scaled to a whole year (May 2007 – May 2008). In order to accomplish this, the value of the recharge rate from each month for each cropping field in 2007 determined using the water balance method was calculated and tabulated. These monthly recharge estimates for the portion of the yearly period leading up the bromide tracer period (May – December 2007) were scaled and added to the recharge rate estimated using the NaBr tracer (January – May 2008) to determine a yearly recharge rate estimate. This approach is further explained in 4.9.2.

3.5 Nitrate Mass Flux

Nitrate mass flux is calculated by multiplying the average porewater nitrate concentration ($C_{aq,ave}$) over the entire depth investigated beneath 1 mbgs at each recharge station by the recharge rate (R) at the associated station as described by:

$$Nitrate\ Mass\,Flux = C_{aq,ave} * R \tag{1.12}$$

The average porewater nitrate concentration calculation within the length of the core is described in Section 3.3.8 by equation (1.6) and the recharge value is described in Section 3.4.2.3. The nitrate mass flux represents the rate that nitrate has passed downward through a plane located below the assumed root zone (1.0 mbgs).

3.6 BMP Performance

In order to assess the performance of the BMP over time, the mass of stored nitrate within the unsaturated zone at several locations were examined over time. The cumulative mass of nitrate (as described by equation 1.5) was plotted with depth below the ground surface for up to five successive coring events at stations 1-9 and 12 which are located in Parcel B in which BMPs are actively being applied. This changes in stored nitrate mass are a key indicator that can be utilized to evaluate the effectiveness of BMPs.

3.7 Upscaling

In order to assess how the BMP was affecting the overall loading of nitrate to the water table beneath each agricultural land parcel, it was necessary to scale the point measurements made at each station to the area of whole field site. With this in mind, a plan was devised as to where to install seven new recharge stations (see Section 4.5). The locations of these new stations were chosen based on predicted conditions that would be found there. These conditions include topography and potential for run-on/run-off, near surface geology and recharge. Following the detail field investigation conducted at each of the new stations, their characteristics relative to the original classification based on the existing sites was reassessed to determine how accurate the upscaling projections were. This information was used to determine how to improve the upscaling approach for future applications.

After this upscaling technique was completed, four extrapolation methods were explored. Each method utilized a combination of the recharge estimates from the bromide tracer test and the un-scaled, non-zero monthly water balance recharge estimates to create a recharge estimate for the one year period leading up to the May 2008 coring event. The stations that did not track recharge using the bromide tracer (stations 5 and 8) used only the water balance estimates of recharge. The yearly nitrate mass loading calculations utilized the depth-weighted average porewater nitrate concentration (see Equation 1.7) of each May 2008 core. The exception was stations 5 which used the results from the last coring event in May 2007. Station 7 is not located in Parcel A or B so its contribution to the loading of Oxford County's land was left out.

The first method of extrapolation method simply took data from all the recharge stations in each Parcel and multiplied the average of the average porewater nitrate concentrations by the average recharge estimate to calculate the average nitrate mass flux. This mass flux estimation was multiplied by the area (*A*) of each Parcel to calculate the nitrate mass loading beneath each agricultural land Parcel as described by:

$$Nitrate\ Mass\ Loading = Flux * A \tag{1.13}$$

The second method was adapted from one designed by Bekeris (2007) and is essentially an extension of the predictions made involving the new recharge stations. It involved subdividing the entire study site into areas that are represented by one of the original 8 station's near surface geology, topography, potential for run-on/off and recharge. The near surface geology and topography were given the most consideration because these were thought to have the greatest influence on groundwater recharge. The near surface geology was determined from the coring events as described in Section 3.3.2. The topography was ascertained from the elevation contours displayed in Figure 4. In general, much of the study site was designated as behaving most similarly to the nearest recharge station but even in some areas within Parcel B, this was not the case. The calculation of loading for this method applied the recharge value measured at each station to its representative area as opposed to using an average recharge value for the entire parcel.

The third method applied the Thiessen polygon approach to graphically interpolate nitrate mass flux measurements at neighbouring stations (Brasel and Reif, 1979). The flux values were weighted based on relative separation between stations. Each station was connected by straight lines. Perpendicular bisectors were drawn on each connecting line to make polygons. The area outlined by each polygon was calculated as a percentage of the total area of each Parcel and assigned the flux value from the station that is contained within that polygon. The calculation of loading in this method also applied the recharge value measured at each station to its representative area as opposed to using an average recharge value for the entire parcel.

The last method to extrapolate point estimates of nitrate mass flux to the field scale was the Contouring approach. The nitrate mass flux values at each station were contoured and the areas between the contours were evaluated as a percentage of the total area within each Parcel and assigned the average of the two confining contour lines. If a contoured nitrate mass flux value was only encompassed by a single contour line, the area within that line was assigned that nitrate mass flux value. This method multiplied the contoured nitrate mass flux values by the area between the contour lines to which each flux value was assigned to produce a total nitrate mass loading estimation beneath each agricultural land Parcel.

These four methods are evaluated in order of increasing complexity and time required to complete. The results section will compare the results of each of these four methods and determine whether complex hydrogeologic conditions have a great affect upon the results of the extrapolation methods.

3.8 Aquifer Vulnerability

The need to protect our aquifer systems is increasingly becoming a higher priority as the realization that safe drinking water is a cornerstone to good health and is not to be taken for granted. Aquifer vulnerability relates to how vulnerable or susceptible a groundwater resource is to contamination from either surface or subsurface sources. This section describes the most popular methods currently in use within Ontario including the Aquifer Vulnerability Index (AVI), the Intrinsic Susceptibility Index (ISI) and the Surface to Aquifer Advection Time (SAAT). The first two methods evaluate how much protection from surface contaminants is offered by the geologic strata that overlie the target aquifer. The SAAT approach combines these elements with a recharge value to estimate how long it takes surface contaminants advecting with recharging groundwater to reach the target aquifer. Each of these approaches are compared and contrasted with each other and examined in the context of some interesting patterns in data collected from pressure transducers in response to two spring melt events at the Thornton Well Field study site.

3.8.1 AVI

The principle of series flow is often applied in electrical and hydraulic applications. Geologic layers can act as the resistance to flow of groundwater. Series flow is shown to be additive across such layers (Bear, 1972). Therefore the total hydraulic resistance, C_q, of groundwater flow across n geologic layers is written as:

$$C_q = \sum_{i-1}^{j} \frac{d_i}{K_i} \qquad (1.14)$$

where d_i is the thickness of the ith geologic unit and K_i is that unit's associated the K-factor. Van Stempvoort et al. (1992) relates this hydraulic resistance approach to the AVI method by taking the log of C_q to express vulnerability in ranges as shown in Table 1. This approach was taken in this study in order to calculate the AVI score for each location. The quotients of each stratum's thickness and K-factor are summed down to the depth of the calculated average yearly water table, converted from seconds to years, then the log is taken of that value in order to get an overall score for that location. The K-factor essentially represents the amount of protection offered by a stratum and is generally related to the negative exponent of the vertical hydraulic conductivity of the layer, except for K-factors greater than or equal to 10^{-6} m/s (see Table 2). Judgment was used for materials that fell between the types listed in

Table 2 (for example silty clay was assigned a value of 10^{-8} m/s). An example of this calculation is given below:

Consider a geologic column that from surface to water table is comprised of 1m of sand overlying 2 m of clay overlying 3m of silty sand. The AVI calculation would be:

$$\text{AVI score} = \log\{[(1/10^{-2}) + (2/10^{-9}) + (3/10^{-4})] / (365 \times 24 \times 60 \times 60)\}$$
$$= 1.8 \rightarrow \text{high vulnerability}$$

The AVI approach, as outlined by the Ministry of the Environment (MOE) (Ontario Ministry of Environment, 2006), calculates a vulnerability score based on the geology from the ground surface to the top of the target aquifer. This method was developed in order to assess the vulnerability of drinking water well capture zones. In order to apply the AVI approach at this study site, all test hole and well logs for the entire study site were gathered and studied. Each log was analyzed and all geologic units were recorded. If any sections of the log were missing, it was assumed that if the material above and below were the same, then the missing section was also the same. However, if the material were different, the missing section was assigned the average value of the materials above and below it.

In many areas of the study site, the unsaturated zone is very thick and accounts for the vast majority of the travel time from surface to the production well. As mentioned in Section 2.2, the study site is primarily comprised of glacial deposits. The aquifer/aquitard units are often laterally discontinuous and missing sections (or "windows") in aquitards are suspected in some areas. These windows allow groundwater to flow from near surface aquifers to lower units and quickly reach the production wells. This "short circuiting" and increased vulnerability is may not be accounted for if assessment methods were calculated to the top of the pumped aquifer unit. For these reasons and in order to equally compare various vulnerability assessment approaches, each method calculates the vulnerability score from the surface to the water table (except for the couple of locations where the ISI method found the aquifer to be confined, in which case the calculation went to the top of the aquifer).

3.8.2 ISI

The ISI analysis method was established by the MOE in 2006 for use in conjunction with the vulnerability assessments of the Clean Water Act modules. This method is similar to the AVI method in that there is a factor that is related to the geologic material it is assigned to which is then simply multiplied by the thickness of that geologic stratum. The sediment types considered were clay, silt, topsoil, sand and gravel with corresponding factors of 8, 4, 3, 2 and 1, respectively. Any strata that were logged as a mix of these sediment types were assigned the value of the most predominant sediment type. For example, sandy silt was assigned a value of 4 (corresponding to the value given to silt). The ISI calculation produces a dimensionless value that can be compared to other point measurements across an area of interest such as a source water protection area. Scores of 0 to <24, 24 to <80 and 80 or greater were grouped into low, moderate and high vulnerability, respectively.

The main difference between the ISI and AVI methods is that in order to apply the ISI method, the target aquifer must first be labeled as confined or unconfined. If the average yearly water table is less than 4m above the top of the aquifer, the aquifer is considered to be partially saturated and unconfined. In this case, contaminants need only to migrate down to the water table so the ISI method only sums the products of the K-factor and thickness of each stratum from the surface down to the top of the water table.

If the water table is located greater than 4m above the top of the aquifer, the aquifer is considered fully saturated and confined. In this case, contaminants must migrate through the overlying confining layers down to the aquifer. These overlying strata provide some amount of protection to the target aquifer. Therefore, the products of each K-factor and stratum are summed down to the depth of the top target aquifer.

What constitutes aquifer material for this study is any sediment comprised primarily of sand or a coarser sediment type. For example, clayey sand was considered aquifer material whereas gravelly silt was not. In order to determine the target aquifer, the method outline by the MOE (2006) was applied to the Thornton Well Field study site. Beginning at the ground surface, find the first aquifer unit that is at least partially saturated and 2.0 m thick. Failing this, locate the first aquifer unit that is at least partially saturated and 1.0 m thick.

In order to determine the depth to the water table at each location, the water levels in the wells were averaged over a one year period. For locations where wells had leveloggers, this meant hourly averages, and for locations where wells did not contain leveloggers, the average of all manual water level readings taken in one year at this location was used instead. The calendar year 2007 was used in most cases except for a few where manual readings were used from 2008.

The ISI method is an indicator of potential vulnerability to an aquifer system but it should be used with caution. Consider an aquifer overlain by (1) a 2.5 m thick marine clay and (2) a 25 m thick silty sand. The ISI calculation would be:

(1) K = 10^{-10} m/s, K-factor = 8, ISI = 2.5 x 8 = 20 → high vulnerability
(2) K = 10^{-4} m/s, K-factor = 3, ISI = 25 x 3 = 75 → moderate vulnerability

However, if we were to evaluate the vulnerability of these two units using travel time (assuming for both a porosity of 0.3 and a vertical gradient of 0.01 m/s) we would get:

(1) T = (2.5 x 0.3) / (0.01 x 10^{-10}) ≈ 238,000 years → low vulnerability
(2) T = (25 x 0.3) / (0.01 x 10^{-4}) ≈ 0.24 years → high vulnerability

This more physically based travel time approach shows that the clay layer provides 6 orders of magnitude more protection than the silty sand layer. This estimate is much more representative of the vulnerability of the aquifer. For this reason, it is suggested that the ISI approach be applied carefully. A similar illustration and discussion was presented by Rahman (2008).

3.8.3 SAAT

The SAAT approach provides a direct estimate of the travel time of surface contaminants to reach the water table. If the target aquifer is determined to be confined (as outlined in Section 3.8.2), then the calculation was completed to the top of the aquifer unit. This approach requires a recharge input to the subsurface. Fields where SAAT calculations were completed used the summed non-zero monthly surplus water balance recharge value from 2008 for the corresponding field. In locations where no water balance calculations were completed, the SAAT calculations used the average of the summed non-zero monthly surplus recharge value for all the fields. A mobile moisture content value (θ_m) is also necessary to calculate SAAT scores. Table 3 outlines general values that were used. Judgment was used for materials that fell between the types listed in Table 3 (for example silty sand was assigned a value of 0.15). An

SAAT calculation to determine the number of years required for surface contaminants to reach the water table (T_{unsat}) (T) is given below:

$$T_{unsat} = \frac{d_{wt}\theta_m}{q_z} \quad q_z \neq 0 \qquad (1.15)$$

where d_{wt} (L) is the average yearly depth to the water table and q_z (L/T) is yearly recharge rate.

3.9 Assessing Vulnerability using Temperature and Hydraulic Head Relationships

The AVI, ISI and SAAT are well established, commonly applied vulnerability methods. However, the AVI and ISI are indexing methods that do not utilize physically measured temporal hydrologic data from the target of the vulnerability investigation. These standardized methods of evaluating vulnerability lack direct, quantified evidence of the conditions in the field and how these conditions can change throughout the year. Since many physical conditions at a site do not remain constant with time, key field parameters were monitored in order to evaluate how vulnerability may be affected by changing physical conditions at the site. Air temperature, groundwater temperature and hydraulic head were monitored at the site to determine when and if selected locations across the site were more vulnerable to surface contaminants at different times of the year, especially during snow melts and run-off events. Groundwater temperature can be used as a tracer of recharging melt water, as can groundwater levels. A sudden increase in groundwater level may indicate a hydraulic connection with recharging water. A sudden decrease in groundwater temperature can indicate the arrival of colder melt water from the surface. Air temperature was measured at the meteorological station and the temperature and pressure within monitoring wells across the site were measured using pressure transducers hung within the wells (see Section 3.3.3).

Table 1. AVI score and associated vulnerability ranking (van Stempvoort et al., 1992)

AVI Score	**Vulnerability**
< 1	extremely high
1 to 2	high
2 to 3	moderate
3 to 4	low
> 4	extremely low

Table 2. K-factors for common hydrogeologic materials (MOE, 2006)

Geologic Material	Representative K-Factor (dimensionless)*	Hydraulic Conductivity (m/s) @75% range**	Highest Hydraulic Conductivity (m/s)
gravel weathered dolomite/limestone (weathered) karst permeable basalt	1	1.00 E-01 1.00 E-06 1.00 E-03 1.00 E-03	0.1
sand	2	0.01	1.00E-02
peat (organics) silty sand weathered clay (<5 mbgs) shrinking/fractured & aggregated clay weathered shale	3	1.00 E-03 1.00 E-04 1.00 E-04*** 1.00 E-05 1.00 E-05***	1.00E-03
silt loess limestone/dolostone	4	1.00 E-06 1.00 E-06	1.00E-06
weathered/fractured till diamicton (sandy, silty) diamicton (silty, clayey) sandstone	5	1.00 E-07 1.00 E-07*** 1.00 E-08*** 1.00 E-07	1.00E-07
clay till clay (unweathered marine)	8	1.00 E-9*** 1.00 E-10	1.00E-09
unfractured igneous and metamorphic rock	9	1.00 E-13	1.00E-13

Notes:
* Representative K-Factors are relative numbers and do not correspond directly to the exponent or index of the observed hyrdraulic conductivity for the geologic material in the group.

** Correspondence with descriptors of observed hydraulic conductivities presented in Freeze & Cherry 1979, Prentice-Hall. Derived using the length of the line to determine the 75% value and rounding to the highest K-Value.

*** Estimated value based on field studies in Ontario

Table 3. Ranges in SAAT mobile moisture content for common hydrogeologic materials

Overburden Texture	**Mobile Moisture Content (%)**
Gravel	5
Sand	10
Silt	20
Loam	25
Clay	40

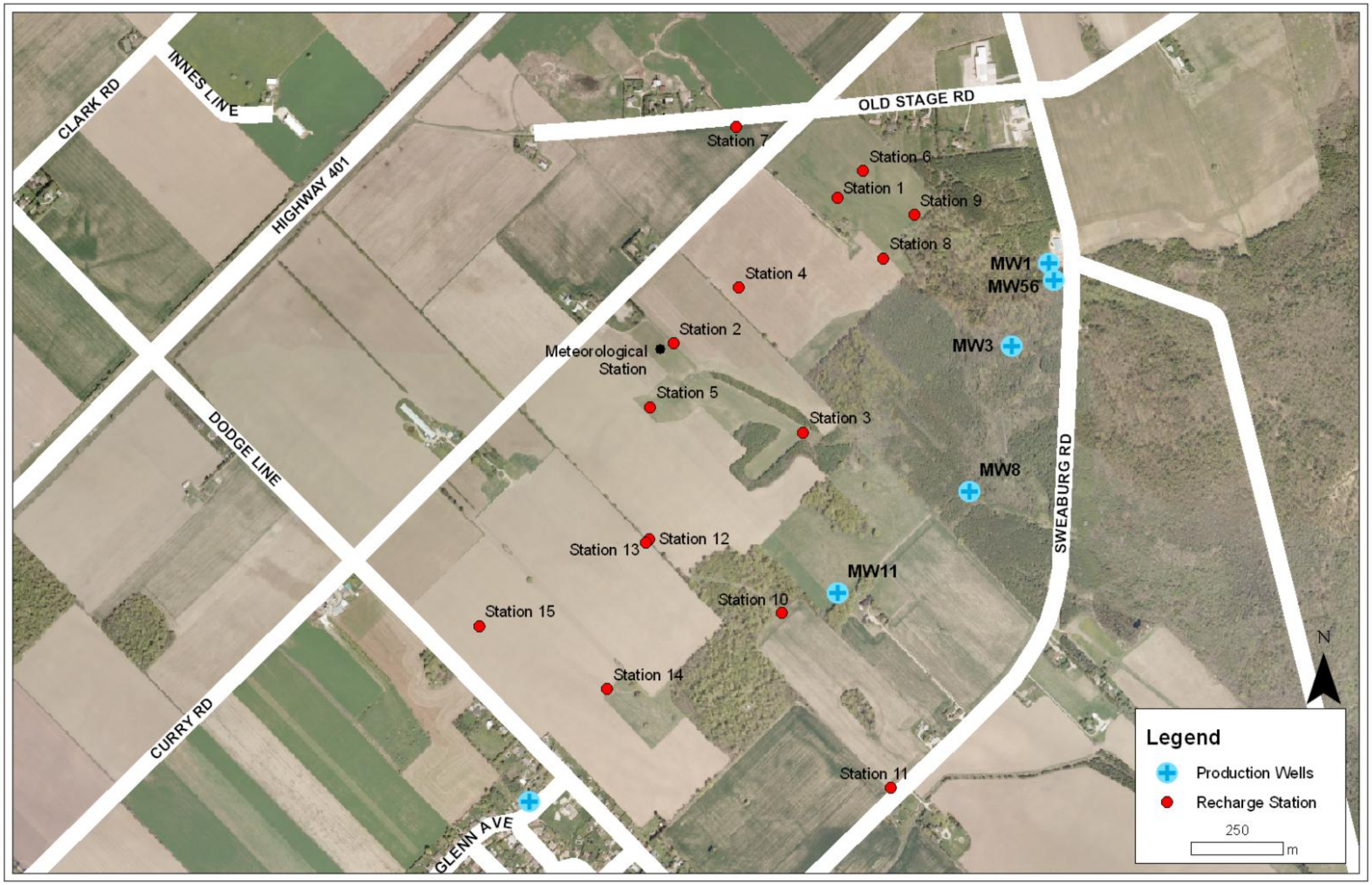


Figure 6. Location of recharge stations, meteorological station and municipal production wells.

Figure 7. Location of stations and corresponding neutron access tubes.

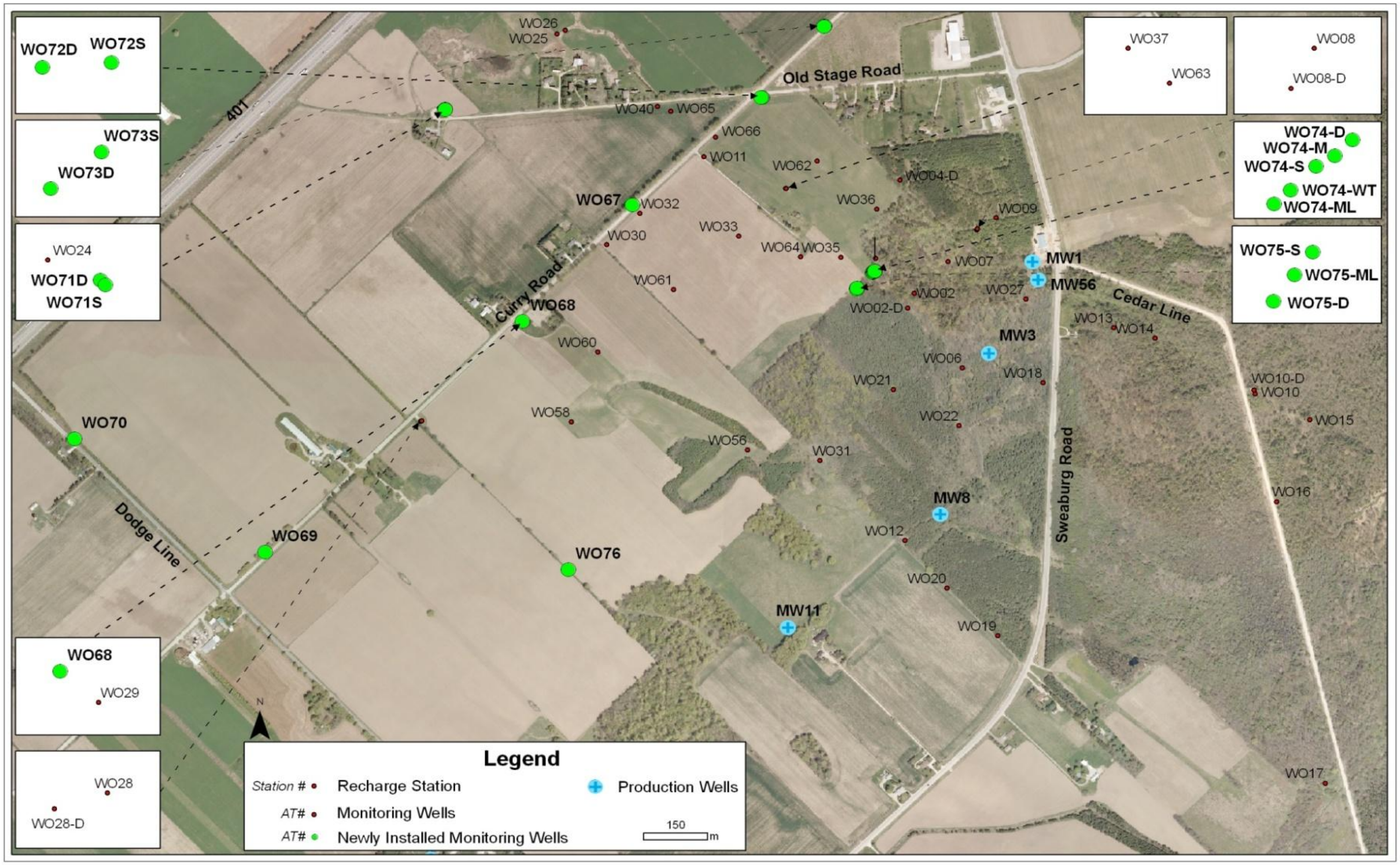


Figure 8. Location of monitoring wells and stations.

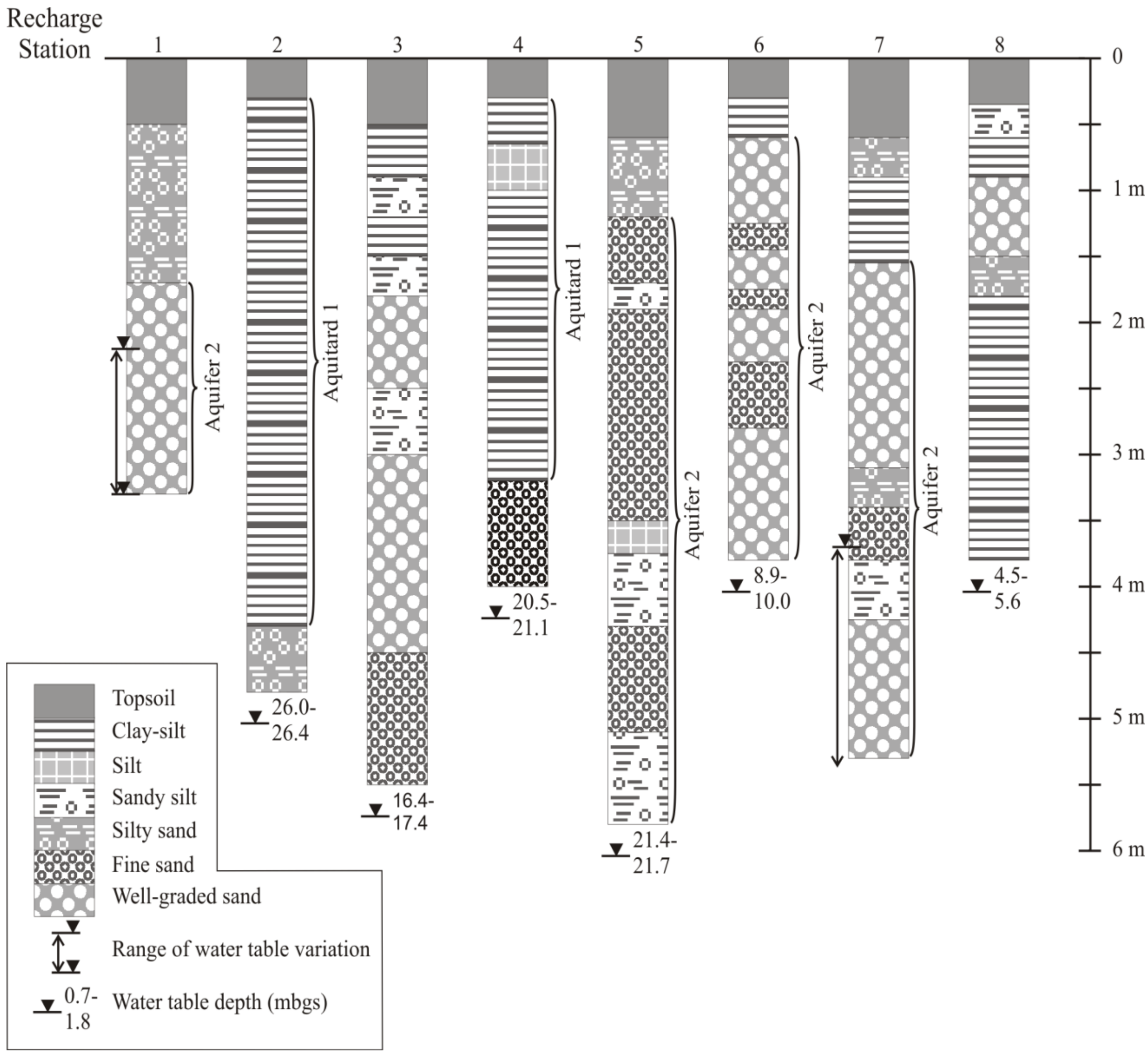


Figure 9. Geology and water table locations at stations 1-8 (from Bekeris, 2007).

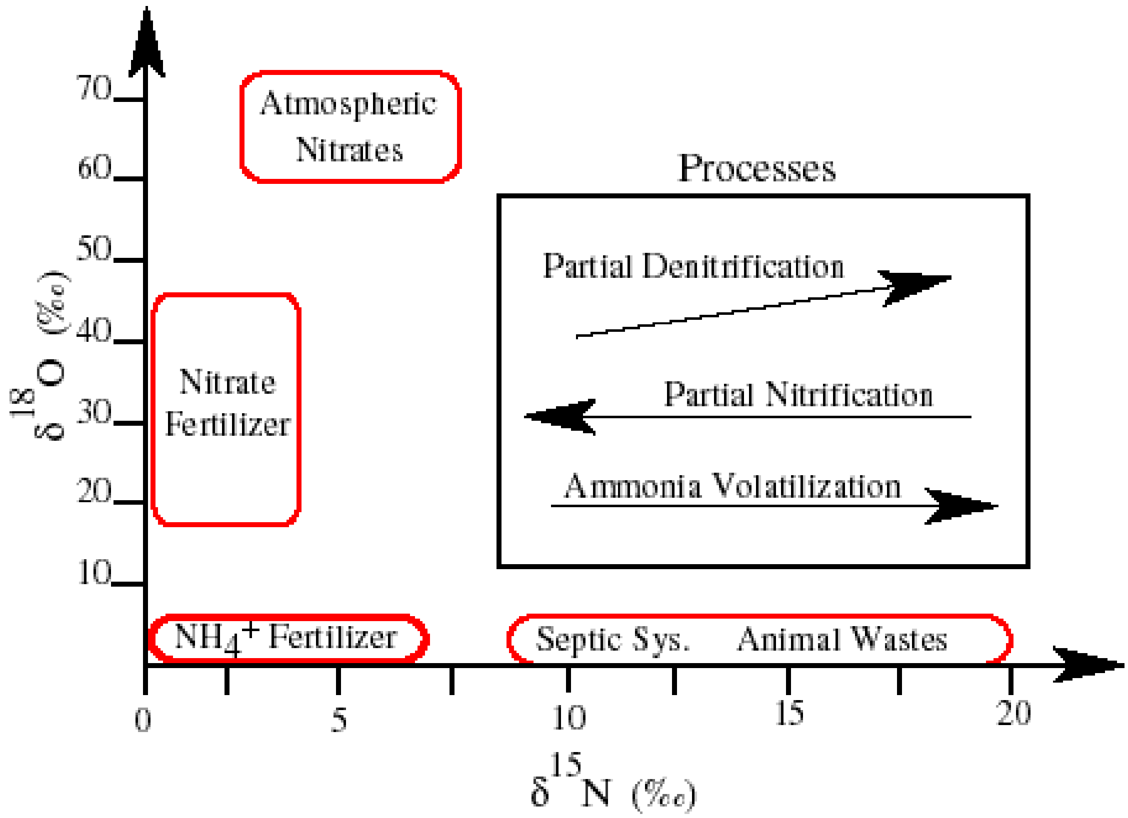


Figure 10. Isotopic fractionation as evidence of nitrate sources (from Bleifuss, 1998).

Chapter 4 Results

This study focused on the effects of nutrient reductions on and the vulnerability of the water table beneath an active agricultural field located within the capture zone of a municipal well field. This chapter will present the results of field, laboratory and computational methods used to evaluate the groundwater recharge, porewater nitrate concentration, nitrate mass loading and upscaling, and vulnerability across the study site.

4.1 Monitoring Wells

While a fairly extensive monitoring well network was already established at the onset of this study, there were several key areas that had not yet been adequately investigated. Seventeen monitoring wells and two Continuous Multilevel Tubing (CMT) installations were completed between November 14, 2006 and January 17, 2007 at 10 locations by Boart Longyear using a Rotosonic mini-sonic drill rig. Seven wells were installed along Curry Road (WO67, WO68, WO69, WO72(S/D) and WO73(S/D)) to provide more water quality data and to enhance the stratigraphic interpretation along the upgradient side of Parcels A and B. Wells installed to the north (WO70 and WO71(S/D)) and to the south (WO76) of Curry Road were installed to refine the groundwater flow direction outside the perimeter of Parcels A & B. Wells WO74 (WT/S/M/D) and WO75(S/D) were installed in a highly conductive area within Parcel B where aquifers 2 and 3 merge. The two CMT installations (at the WO74 and WO75 locations) are comprised of multi-level wells with 7 screened intervals that extended as deep as ~15 mbgs. Figure 11 depicts the locations of all the new monitoring wells, Table 4 displays the details of these new wells and the geologic logs are contained in Appendix B. Survey data is found in Table 5. Survey data can be in Table 5.

4.2 Hydrogeologic Conceptual Model

Padusenko (2001), Haslauer (2005) and Bekeris (2007) described the conceptual geological model at the study site. Each one built upon the former model as new stratigraphic records were determined through geologic coring. These original conceptual models were based upon a four aquitard, five aquifer system. The recent coring campaign during the monitoring well installation program (described above) has lead to an updated conceptual model that has been able to determine where some of the “windows” in aquitard units are located which provide a direct hydraulic connection between Aquifers 2 and 3 in the vicinity of WO37. The geologic logs from the new monitoring well installations (Appendix B) were utilized in updating the conceptual model. Three cross-sections are displayed in Figure 12, Figure 13 and Figure 14.

Section A-A' runs along Curry road from the intersection of Dodge Line to just east of WO73. It displays Aquifer 2 pinching out beneath the glacial outwash channel where Aquitards 2 and 3 merge. Also at that depth beneath the glacial outwash channel there is a discontinuity in Aquitard 3 which provides a direct connect between Aquifer 2 and 3. Section B-B' also runs parallel to Curry road but it is about 500 m to the south-east. B-B' depicts a direct connection between Aquifers 1 and 2 and also between Aquifers 2 and 3 beneath Parcel B near the outwash channel. Section C-C' runs perpendicular to both A-A' and B-B' which extends from WO40 through the outwash channel to Sweaburg road. It displays two small windows connecting Aquifers 1 and 2 and the nearly complete merging of Aquifers 2 and 3 as Aquitard 3 is only thinly present near the north and south ends of the section.

4.3 Groundwater Level Monitoring

Hydraulic heads were contoured for water levels measured in wells screened in Aquifer 2 (Figure 15) and Aquifer 3 (Figure 16) in January 2007 and May 2008. The raw data is contained Appendix C. These two times were selected in order to compare the extremes in dry and wet conditions that existed at the site. In January, the Aquifer 2 wells measured were mainly located within or near to the glacial outwash channel, in Fields 6 and 7. In this area, the groundwater flow direction is predominantly east to southeastward along the outwash channel (outwash channel featured in Figure 5). Wells screened in Aquifer 3 situated within each of Fields 3b, 4, 5, 6 and 7 were measured and the contoured data display an eastward flow direction across the study site. Sixteen months later, several more wells had been installed and were monitored. The potentiometric map from the wells screened in Aquifer 2 displayed eastward flow near the northern edge of the study site, which turned southeastward to flow down the outwash channel in the southeast of the site. A southeastward groundwater flow path within Aquifer 3 was observed north of Curry road, which turned eastward as it flowed throughout the study site south of Curry road.

The hydraulic head in Aquifer 3 was generally slightly higher than in Aquifer 2 suggesting a component of upward groundwater flow. This upward gradient decreases as distance to the supply wells decreases, as would be expected because the supply wells are screened within Aquifer 3. A downward gradient was measured near the end of Fields 6 and 7 where WO74 and WO75 are located. The potentiometric surface was significantly (~1-2 m) higher in Aquifer 3 in May 2008 than January 2007. This is a seasonality effect of the spring recharge that raises the water table across the study site. Flow directions remain about the same throughout the seasons.

4.4 Groundwater Geochemistry

One method of assessing the influence of the nutrient reductions on the subsurface water quality is to compare changes in groundwater nitrate concentrations throughout the study area. Contoured nitrate concentrations for sampling rounds in October/November 2007 and May 2008 for wells in aquifers 2 and 3 are found in Figure 17 and Figure 18.

Nitrate concentrations in Aquifer 2 tended to be the most elevated in the northwest region of the woodlot area near the production wells (see Figure 17 and Figure 5 for location of woodlot). Outside of the woodlot, lower nitrate concentrations were typically found within the outwash channel which tended to increase with distance from the margins of the channel. The highest nitrate concentration measured during the study period occurred in May 2008 at 17.9 mg NO_3-N/L at WO73-D in the northeast corner of the study area. WO37 at station 1 had the highest concentration measured during the October/November 2007 sampling round at 15.5 mg NO_3-N/L, followed closely by WO35 at station 8 at 14.7 mg NO_3-N/L. The area around station 8 has had persistently high nitrate concentrations, possibly because historically it had been used as both a cattle pasture and manure pile storage area (Dave Start, personal communication). The lowest concentration outside of the woodlot was 2.7 mg NO_3-N/L which was measured at the end of the glacial outwash field at WO74-WT in May 2008. On average, May 2008 yielded lower nitrate concentrations at 8.5 mg NO_3-N/L compared to the 10.7 mg NO_3-N/L measured during the October/November 2007 sampling round. This is likely a seasonal effect due to the presence of low nitrate melt water having recently recharged and having impacted water quality of shallow wells in the May sampling round. The nitrate concentrations within Aquifer 2 are fairly uniformly distributed throughout the study area with no real plume shape or pattern present.

Nitrate concentrations in Aquifer 3 (Figure 18) display more of a regional plume shape trending from the northwest region of the study area. It is believed that one source of the nitrate mass within Aquifer 3 originates somewhere to the northwest of Curry Road. As can be seen in cross sections A-A' and B-B' (Figure 12 and Figure 13), Aquitard 3 pinches out, providing a direct connection for groundwater to flow upward from Aquifer 3 to 2 under the vertical gradient (described in Section 4.3). The plume's fairly constant shape and concentration (ranging about 10-16 mg/L) for both sampling events suggests little seasonal effect. This behaviour is expected in a deeper aquifer unit.

Overall, the nitrate concentrations shown in each of Figure 17 and Figure 18 are fairly uniform with no high spikes, typical of non-point agricultural nitrate contamination. However, the nitrate concentrations shortly after the large spring melt in May 2008 within Aquifer 2 are significantly lower than in January 2007, especially within the glacial outwash channel and near stations 3 and 5. This is likely due to the influx of relatively low nitrate (~3 mg NO_3-N/L) melt water streams that ran down and recharged into both the outwash channel and along a low elevation path through station 5 and past station 3. The nitrate concentrations are also generally lower in the woodlot near the supply wells. One reason for this is likely due to the lack of historically applied nitrate at the surface in this area. Low nitrate water recharging from the surface in the woodlot mixes with the groundwater due to the downward gradient and the hydraulic connection between Aquifers 2 and 3 in this area (see cross section C-C' on Figure 14) which lowers the overall nitrate concentration beneath the woodlot and at the supply wells.

Nitrate concentrations have been monitored over time at each of the recharge stations and are plotted for stations 3 and 8 in Figure 19 and the rest of the stations in Appendix D. The nitrate concentrations at stations 2, 3, 6 and 8 show a small but significant improvement between the most recent sampling round and the round before it. The nitrate concentrations at the other stations typically oscillated slightly higher or lower, depending on the season in which the sample was taken. Haslauer (2005) noted that nitrate concentrations measured at the study site in 2005 were somewhat higher than in 2003, and distinctly higher than in 1998. However, results from 1997 through 2008 (see Figure 20 and Figure 21) seem to indicate that this trend may be beginning to taper off. The upper range in average nitrate concentrations was reached in 2005 and since appears to have leveled off. The small variations since 2005 are likely primarily due to seasonality. As the time elapsed since BMP implementation increases and more clean water recharging from the surface reaches the water table, the average nitrate concentrations beneath the water table are likely to at least cease to increase and perhaps begin to decrease. This pattern needs to be carefully considered since the list of wells sampled each year were not all the same and the seasonal variation in nitrate concentrations may slightly affect the overall averages from year to year.

Chloride concentrations have been monitored over time at each of the recharge stations and are plotted in Figure 19 and in Appendix D. Recent chloride concentrations at each of the stations, except 1 and 5, have declined to varying degrees. This may indicate the change over from mixed manure/commercial based fertilizers that have some excess Cl in them to purely commercial fertilizer which are Cl free. The fact remains that nitrate leaching is occurring but the decrease in Cl suggests that perhaps the source may now be commercial fertilizer as presently the legacy of Cl leaches away. Another source of Cl may also be due to road salt application on highway 401 which is a few kilometres to the north of the study site.

Results from the discrete sampling port of the CMT wells (see Figure 22 and Figure 23) display a more definite trend than the results from the long well screens of the monitoring wells at the stations. These CMT wells are located just upgradient of the woodlot, within the outwash channel. The water table at this location is typically fairly shallow at about 3-4 mbgs. The small sampling ports allow for discrete depth sampling, which decreases the amount of mixing with water from a wide range of depths. The data indicate significantly lower NO_3 concentrations near the water table (~4 mg/L) increasing to a uniform value of approximately 13 mg/L through the remaining depth of the aquifer. This may indicate the presence of low NO_3 water infiltrating to the shallow system as a result of the nutrient BMPs. The results also display how the nitrate concentrations vary somewhat from month to month, suggesting that seasonality may play a key role in nitrate concentrations near surface.

The majority of the wells at the study site have screens that are 10' (3.0 m) in length. This large screen interval allows for a great deal of mixing of fresh, recharging water with aquifer water. Mixing in the long wells screens masks the true impact of BMPs and so it is recommended that multi level short screen wells, such as CMT wells, be used to monitor non-point source contamination in an agricultural setting.

4.5 Nitrate Isotopic Analysis

Water collected in August and September 2007 was analyzed for ^{15}N and ^{18}O in nitrate and the results are found in Table 6 and plotted in Figure 24. The majority of the sampling locations had isotopic signatures that plotted within the enriched range of NH_4^+. This signature suggests the source of N is primarily from commercial fertilizer. However, a few of the sample points had ^{15}N signatures that were too enriched to there seems to be from NH_4^+ fertilizer. This and the fact that all of the samples plotted near the enriched end of the NH_4^+ fertilizer range suggests that at least a small degree of mixing of nitrate laden water from both manure and fertilizer sources. Manure had not been spread for at least 5 years within Parcel B but has been spread consistently in Parcel A and on the Old Stage Road field, both of which are upgradient of the majority of the wells that were sampled. While 5 years is approximately the average travel time for surface water to recharge to the water table within Parcel B (see Section 4.15.3), groundwater that is recharged from manure-applied fields to the north of Curry Road likely has advected beneath Parcel B. It is most likely that major source of the nitrate is from commercial fertilizer but that the slightly enriched

^{15}N signature suggests that some degree of blending with groundwater containing manure-based nitrate is occurring.

4.6 Climate and Hydrology

4.6.1 Meteorological Station Data

Meteorological data were collected from the on-site meteorological station during the course of this study (see Section 3.1.1). The average historical yearly precipitation and average daily air temperature in Woodstock was 950 mm and 7.5 °C respectively for the periods 1971-2000 (Environment Canada, 2008). The annual precipitation measured at the site in 2005, 2006, 2007 and 2008 was 961, 1168, 835 and 1288 mm respectively. The average annual temperature measured at the site in 2005, 2006, 2007 and 2008 was 8.2, 8.9, 8.2 °C and 7.3 °C. Thus, the last several years have generally been both wetter (except 2006) and warmer than on average. The average daily air temperature and precipitation data recorded from January 2007 through May 2008 at the meteorological station are shown at the bottom of Figure 25. The first five months of 2008 recorded a total of 450 mm of precipitation (50 mm of which fell on the last day of May) which is 28% higher than the 350 mm that fell on average in Woodstock during the same time frame between 1971 and 2000 (Environment Canada, 2008). However, cooler than average temperatures of -3.5°C were measured at the site during that time compared to historical temperatures of 1.5°C (Environment Canada, 2008). Other noteworthy climatic observations that occurred during the course of this study include the extremely variable precipitation measured in February 2007 and 2008 of 6.1 and 107.7 mm respectively compared the historical average of 53.7 mm (Environment Canada, 2008).

The data shows that 2008 was an exceptionally wet year with several sudden and massive warming periods in the early part of the year. This above zero temperature caused a rapid melting of snow that had accumulated at the ground surface. This large volume of cold melt water began recharging into the subsurface. As a result, interesting trends in water level elevations and temperatures were detected by pressure transducers hung within monitoring wells, which are discussed below.

4.6.2 Groundwater Pressure and Temperature

Constantz et al. (2002) showed that streambed temperatures could be used to characterize stream/aquifer exchange in ephemeral streams in the Western United States and it was hypothesized that these methods could be used here. In this study, the effect of ephemeral melt water streams on water levels and groundwater temperatures were monitored at several of the recharge stations from January 1, 2007 to May

31, 2008. Precipitation, water levels, air and groundwater temperatures at each station and other selected locations are plotted in Figure 25 through Figure 30 and in Appendix E. These events included rapid warming periods with air temperatures rapidly rising above 0 °C leading to significant snow melting and groundwater recharge. The responses at each of these locations can be categorized based on the magnitude of water level fluctuation and the time lag between the peak air temperature and water level. The responses were lumped into one of three categories: fast, moderate and slow response, which would correspond to high, moderate and low vulnerability to contamination respectively.

4.6.2.1 Fast Response

The response in hydraulic head and groundwater temperature to the increase in air temperature at each of stations 1, 6, 9 (at monitoring wells WO63, WO62 and WO36, respectively) and at monitoring wells WO11-6, WO40 and WO66 was very fast. Each of these monitoring wells are screened at relatively shallow depth (except WO63), within the coarse sediments of the glacial outwash channel. The water table is on average only 5.2 mbgs, ranging from 2.6 to 9.3 mbgs. These wells are also all situated within topographically low areas (except station 6 which is on the side of a hill) which collect run-on surface water. The data from station 1 are presented in Figure 25 and Figure 26 for illustrative purposes. At specific times during the year, the hydraulic head at these locations fluctuated significantly due rapid infiltration through coarse sediments to the near surface water table.

The responses during the melt events were very interesting as large increases (~1 m) in water level typically followed less than 24 hours after a spike in air temperature. During major melt events, an ephemeral stream typically flows directly over WO37, WO40, WO63 and the other locations (see Figure 31 through Figure 33). The January 2008 melt events were characterized by warm air temperatures and melting snow. This was followed by significant pressure increases but not groundwater temperature decreases. The February and March melt events were characterized by rapid and significant pressure increases as well as rapid groundwater temperature decreases which initially recovered quickly but in later events recovered more slowly. These later temperature responses likely illustrate the arrival of larger quantities of colder melt water which caused the sudden decrease in temperature. The slow increase in temperature that followed could represent the shallow water table coming into thermal equilibrium with deeper or warmer water from non-recharge areas advecting past the monitoring well. The melt events in late March and early April resulted in significant pressure increases as well as temperature decreases.

There was concern and some evidence that some well casings were leaking during melting events and flooding (i.e. WO37). If the sudden decreases in temperature observed in wells were due to leakage, it would be short lived because of the local nature of this water input, whereas more regional infiltration would have temperatures that would remain lower for a longer period of time. WO40 is an excellent example of how recovery of groundwater temperatures is slow following cold melt water events. These responses in temperature and pressure are potentially excellent localized indicators of aquifer vulnerability and may also help identify whether some of the wells were improperly constructed as discussed by McCutcheon (2008).

4.6.2.2 Moderate Response

A moderate response was measured in hydraulic head and groundwater temperature due to an increase in air temperature at stations 3 (Figure 27 and Figure 28), 4 and near 8 at wells WO56, WO61 and WO64 (Appendix E) respectively. The water table at these stations is located at an average 14 mbgs except at station 8 where it is just 5 mbgs but a 2 m thick clay silt layer is present near surface. As a result, these stations featured slightly slower and less dramatic responses than the “fast” responding wells. Throughout the year, each of these plots displayed several sharp variations in hydraulic head. These variations were typically less pronounced in relative change in hydraulic head than the “fast” responding wells. Both of stations 4 and 8 had virtually no significant variations in temperature throughout the year. Station 3 on the other hand, did display similar decreases in groundwater temperature to the “fast” wells during the 2008 melts, but not at all during the 2007 melts. Also, since the relative change in hydraulic head was significantly lower than the “fast” responding well, WO56 at station 3 was labeled as a “moderate” responding well location.

The responses during the melt events were again very interesting, though somewhat different than at the “fast” responding wells. Typically peak water levels were measured a day or two after peak air temperature were measured, with moderate water level increases of about 0.3 m due to spring melt events. Station 3 did not show a significant response in pressure or temperature during the January winter melt unlike the “fast” responding station 1. In early February, the water levels rose significantly several times and the corresponding downward spike in temperature dissipated in a similar fashion to that of station 1. During the late March spring melt, a rapid drop in temperature was recorded with a rapid recovery and a rapid rise in water level was followed by a slow recovery. This behaviour is different from station 1 where groundwater temperature remained depressed for a longer period of time. This suggests that station

3 may be vulnerable but that probably the shorter duration temperature changes indicate that leaks in the well casing allowed water from the ephemeral stream (see Figure 32 and Figure 33) that passed over station 3 to enter the well and decrease the temperature. For example, February 5, 2008 spring melt reveals the major decrease in well temperature occurred just an hour after the peak air temperature but the peak hydraulic head was not reached for another 37 hours. In this instance, the effects of natural infiltration are still noticeable, but the interpretation is complicated due to the leak.

4.6.2.3 Slow Response

The response in hydraulic head and groundwater temperature to the increase in air temperature at station 2, well WO60 (Figure 29 and Figure 30) and at stations 12 and 13, well WO76 (Appendix E) was slow or barely detectable. The monitoring wells at these locations are characterized by mixed coarse and fine sediment layers and very thick unsaturated zones with an average depth to the water table of 28 m. These locations featured <0.2 m increase in hydraulic head following spring melt events. The lag time between the peak air temperature and the peak increase in hydraulic head was about 2 weeks at stations 12 and 13 and no clear relationship could be determined at station 2. The shape of the water level plots are fairly sinusoidal with the peak occurring late May/early June due to the slow arrival of recharging melt water from the surface and the low point occurring in late January/early February due to the lag time associated with the low amount of recharging water during late summer. The thick unsaturated zone may dampen out any temperature or pressure signature from what little recharge occurs at these locations. Changes in water levels may be due to infiltration elsewhere in the aquifer resulting in regional rises in water levels.

4.6.2.4 Implications

It is clear that responses in pressure and temperature can be good indicators of how the subsurface responds to hydrologic events involving groundwater recharge. It is recommended that temperature and pressure in shallow wells be carefully monitored during these types of hydrologic events. This monitoring will allow for the location of fast responding areas and compromised well construction. Evaluating pressure and temperature data response times within monitoring wells is recommended as a method to estimate how long it takes recharge from the ground surface to arrive at the water table. Furthermore, the amount of time temperatures remain depressed and recovery times following melt events may provide insight into the relative amount or aerial extent of local recharge. The longer the time required to return to pre-event temperatures likely indicates greater quantities of recharge water reached the water table in the vicinity of the well.

4.7 Upscaling

4.7.1 Selection of Additional Recharge Station Locations

One of the main objectives of the field investigations was to develop a strategy to upscale local or point information collected at each of the recharge stations to the larger field area. The process involved classifying regions in the broader landscape, based on the physical setting that would be similar to conditions encountered at one of the eight original recharge stations. The goal here is to be able to expand the local scale information over a larger region without the need for extensive additional site investigations. The approach taken here was to first select seven new recharge station locations within the study area (based primarily on topography and general geologic setting) that would have similar characteristics to one of the original eight stations. The new stations are situated in both the Parcel A and B fields as shown in Figure 6. In order to evaluate how appropriate the selection and classification was, detailed field work including vadose zone coring, installation of neutron tubes and the application of bromide tracer for recharge estimation was conducted at the new stations. The new data were used both to upscale the estimate of nitrate mass loading within Parcels A and B, and also to determine how accurate the site selection process had been. The classifications of the stations are shown in Table 7 and discussion of the upscaling process follows in Section 4.11.

4.8 Stratigraphy at Recharge Station Sites

The shallow composite geologic logs presented in Figure 9 and Figure 34 were compiled using available borehole logs from each recharge station. The location of all 15 recharge stations is shown in Figure 6 and their topography and surficial geologic conditions are summarized in Table 7. The unsaturated zone extended deeper than depicted in the logs at most stations. The nature of the shallow stratigraphy plays a significant role in controlling recharge and nutrient mass flux at each location, which are critical components of this investigation. The subsurface geology, which was available from the boreholes drilled in March 2005 (Bekeris, 2007) through May 2008, is described below. For reference, the main hydrostratigraphic units are indicated on the geologic logs where possible.

The shallow stratigraphy of each of the stations was generally consistent with the quaternary geology map shown on Figure 5. Stations 1, 6 and 9 lie within the glaciofluvial outwash channel which were dominated by sand and gravel, with some silt layers at stations 6 and 9. The average depth to the water table of Aquifer 2 during the current study period was 2.6, 2.7 and 9.3 mbgs at stations 1, 9 and 6 respectively. Station 7 is also situated within the outwash channel, just north of Curry Road. Its geology consisted of sand with some clay layers near ground surface. The average depth to the water table was 5.1 mbgs at this site.

The clay-silt dominated Zorra till (shown in Figure 5 and designated as Aquitard 1) comprised the shallow stratigraphy at stations 2 and 4. The till at station 2 overlies unsaturated silty sand which overlies a layer of clay, silt and sand interpreted to be Aquitard 2. Sand and silt continues with depth except between 24 to 28 mbgs where clay and sand layers form Aquitard 3. A similar stratigraphy was found at station 4 except that Aquitard 2 was not encountered.   The average depth to the Aquifer 3 water table was 26.0 and 20.6 mbgs at station 2 and 4 respectively.

The clay-silt till was not found at station 5 but was dominated by layers of fine sand, silty sand and silt down to Aquifer 3 where the average depth to the water table was 21.2 mbgs. At Station 3, 2 m of clay-silt till overlay silt and sand, which overlay thin clayey layers at 6 and 8 m which are interpreted to be Aquitard 2. At greater depths, sand and silt layers associated with Aquifers 2 and 3 and Aquitard 3. The average depth to the Aquifer 3 water table is 17.0 mbgs.

Station 10 is located on a slope, near municipal supply well #11 and is underlain by fairly uniform, dry sand corresponding to Aquifer 2. Station 11 is found at the southwestern-most corner of Parcel A. The unsaturated zone is composed of sandy silt from surface to about 4 mbgs followed by finer mixed silts and clays interpreted to be Aquitard 4. Saturated material was encountered during borehole drilling in November, 2007 at roughly 5 mbgs, and was interpreted as being a localized perched system. From contoured water level elevation plots created by Padusenko (2001), it is suspected that the water table is located at approximately 20 and 4.5 mbgs for stations 10 and 11 respectively, which was beyond the depths of the core collected at station 11.

Stations 12 and 13 are located on either side of a narrow grass strip separating Field 2 in Parcel B from Field 3 in Parcel A. The near surface stratigraphy is comprised of coarse sand and gravel, which is interpreted as Aquifer 1. The water table was not encountered during coring of these stations and WO76, located about 4 m from each station, had a depth to water of 30.4 mbgs. The core log from WO76 is mainly comprised of alternating layers of sand and silt, making interpretation of distinct aquifer and aquitard units difficult.

Stations 14 and 15 are located in Parcel A. They are comprised primarily of loose sand associated with Aquifer 2. Station 14 is located in a deep, southward sloping gulley. Although the borehole drilled at station 14 encountered wet sand at approximately 9.1 mbgs, the water table is thought to be much deeper at around 22 mbgs (Padusenko, 2001). The boreholes at station 15 did not encounter any wet materials and the water table there is thought to be located approximately 30 mbgs (Padusenko, 2001).

The near surface geology varied significantly across the site. A good example of this is the stratigraphy recovered from cores approximately 10 metres apart at station 12 and 13, where a clay layer was found near surface at the latter but not the former. Overall, the majority of the site is overlain with fairly permeable sediments.

4.9 Estimates of Groundwater Recharge

4.9.1 Water Balance Method

The water balance method employed an empirical equation (Allen et al., 1998) to estimate recharge at the field site by using data collected at the meteorological station. ET was calculated using field specific crop data which was then subtracted from precipitation data to estimate recharge. The water balance method is described in Section 3.4.2 and detailed information pertaining to the method is found in Appendix A. Some of the parameters used to estimate ET include air temperature, atmospheric pressure, relative humidity, solar radiation and wind speed. A daily reference evapotranspiration value (ET_o), corresponding to the anticipated potential ET for a standard grass crop assuming a continuous supply of soil water was available, was calculated using these parameters. The estimation of potential ET value during conditions where the soil is frozen or snow covered is difficult because it violates the assumption of a sustained grass reference crop (Allen et al., 1998). As suggested by Allen et al. (1998) for these conditions, an average ET value of 1 mm/day was used. In this study, these conditions were assumed to correspond to the period in which average air temperatures were below zero degrees Celsius.

The effect of melt water and ephemeral streams were not able to be incorporated into the water balance estimation for recharge. These equations are described in further detail in Section 3.4.2.1 and sample calculations are found in Appendix A. It should be noted that subsurface geology and soil characteristics do not influence the empirical equation. While the meteorological station was located in a flat, open area, one minor potential source of error in the water balance calculation is that it was assumed that all meteorological parameters were uniform across the study site. A major assumption made in employing this empirical water balance method is that run-on/off component was zero. Observations made throughout the course of the study would suggest that run-on/off is likely only a factor during the winter and spring snow melt events, which will be discussed later.

From field to field, changes in ET were mainly caused by variations in cropping patterns since precipitation and climatic conditions were was assumed invariable in space. Therefore, the final water balance estimates for several fields that were cropped the same were equal. The crop types that were planted during the water balance estimates in 2007 and 2008 were corn, soybeans, Romano beans, winter wheat and grass, each of which have different estimations of ET rates.

Table 8 displays the results of the water balance recharge estimate which shows how the calculations of recharge varied in 2007 from a low of -134 mm/yr under a grass crop to a high of 116 mm/yr with corn planted. Negative recharge values are interpreted as a decrease in soil water storage occurring as a result of a lower total magnitude of precipitation than ET estimated during these periods. The water balance method of calculating potential ET assumes an unlimited supply of soil moisture in the vadose zone, so the negative values may be less negative than shown. Winter precipitation could be expected to increase groundwater recharge. However, increases in infiltration in some cases can trigger vegetation growth which extracts the additional water before it becomes recharge (Smith et al., 2000; Scanlon et al., 2005). For this reason, water balance estimates of recharge that were calculated as negative were considered zero. In 2008, recharge values ranged from 315 under a soybean followed by a winter wheat crop to 480 mm in fields planted with corn (see Table 9). The yearly precipitation measured at the site in 2007 was 835 mm which is significantly less than the 1288 mm measured in 2008. At the time of this study, November and December 2008 precipitation had not yet fallen. Therefore, the approximate average of historical precipitation and evapotranspiration measured at the site during the periods of this study and the study completed by Bekeris (2007) were used to approximate recharge values of 80 and 40 mm for November and December, respectively. The average historical precipitation measured in Woodstock between 1971 and 2000 by Environment Canada (2008) is 954 mm. 2007 was a dry year and 2008 a significantly wetter than average year.

Figure 35 through Figure 39 display the precipitation and estimations of potential ET in each of the fields within the study site. The potential ET roughly plots as a sinusoidal wave with the high point in mid June when total solar radiation is high and crops are growing and transpiring. The low point was in mid January when total solar radiation is low and fields are snow covered. Evapotranspiration tended to be lowest in fields planted with corn and highest in the fields where grass grew. While precipitation varied significantly between 2007 and 2008, the highest amount of precipitation typically fell in the early spring and later fall. This peak precipitation period also corresponds to the low ET period, thereby making it the peak period for recharge. Figure 40 displays the monthly water balance recharge estimates from May 2007 to May 2008 for stations 1, 3, 5, 6, 8, 9 and 2, 4 which were planted in grass and winter wheat/corn respectively. Several of the months had a net recharge of zero. The distribution of precipitation during this time period was not consistent with historical distribution patterns. No recharge was estimated during May 2007 and April 2008 as these months were atypically dry.

The calculation of ET relies on both physically collected meteorological data and empirical crop coefficients or other parameters based on literature values such as root depth, crop height, crop growth stage lengths and soil water availability. Literature data are utilized because the measurement and monitoring of some parameters in the field was very impractical. Furthermore, the empirical formulas also do not account for the massive amount of recharge that occurs at the site due to the spring melt. As a result, the assumptions required to calculate actual ET and the ability of the water balance method to account for the timing of recharge due to snow melt events limit the accuracy of water balance method for the estimation of recharge at a sub annual rate. The calculation of recharge for the snow covered parts of the year is especially uncertain as literature describing how the water balance method should handle this process is limited (Allen et al., 1998). The water balance method is really only useful under ideal conditions which typically are not met during the spring, summer and winter. The water balance method tends to overestimate ET, not capture snow melt events or account for run-on and thus underestimates recharge.

4.9.2 Bromide Tracer Method

A sodium bromide tracer was evenly applied at ground surface in a 3 by 3 m area at stations 1-4, 6, 9-15 in January 2008 (see Section 3.2) in order to attempt to directly measure local recharge rates. Cores were collected at each of the recharge stations in May 2008 and the subsurface distribution of bromide was determined. Samples collected from these cores provided the soil moisture content data (see Appendix F) utilized in the calculation of the recharge estimates. The estimates of recharge are listed in Table 10.

Vertical profiles of the cumulative bromide mass and bromide concentration profiles based on cores taken in May 2008 for station 4, 6, 10 and 15 are shown in Figure 41 and profiles for all stations are found in Appendix G. Nearly all the cores were able to clearly capture the centre of bromide mass, which is evident by the shape of the bromide concentration profiles which display a clear peak in bromide concentration near the surface. However, the plots at stations 3 and 9 do not display quite as distinct a peak. Instead, there are a couple of higher peaks but the centre of bromide mass utilized to determine the recharge rate is still able to be calculated. During the time of the tracer test, a couple of significant melt events occurred and a melt water stream was witnessed flowing close to or over each of stations 1, 3 and 9 where the 3 by 3 m test area was located. It is believed that lateral flushing washed away some of the bromide tracer within these areas by surface runoff waters, as evidenced by the low percent of recovered tracer (see Table 11) and low bromide concentration within these cores. While the percent recovery is a bit low and the shape of the bromide concentration peaks are not quite as defined, it is still believed that the bromide tracer remains fairly accurate and the most direct method to estimate recharge at these locations.

Another interesting finding was the large discrepancy between bromide recovery and vertical position of the centre of mass at neighbouring stations 12 and 13 (see Table 11). One likely explanation of this large difference may be attributed to the winter wheat that had been planted at station 12 the preceding autumn, which had been growing throughout the entire bromide tracer test period. At the time of coring in May 2008, it was noted that the wheat within the 3 by 3 m test area had only grown to about half the height of the surrounding wheat. Conversely, no crop had been planted or grew during the time of the tracer study at station 13. Kung (1990) has shown that growing crops are able to take up bromide during times of growth. Available water within the root zone is also taken up by the plant roots which may have retarded the bromide pulse within the recharging groundwater. Another possible reason as to why the results of the bromide tracer test varied so greatly between the two nearby station could be varying near surface geology. Within a glacial moraine deposit, the spatial distribution of geological units can be extremely variable. The core taken at station 13 displayed a thin, 0.2 m thick clay layer just beneath the top soil. This layer may have acted in a similar manner to the clay layer at station 2 which likely promoted horizontal subsurface flow and thus reduced local recharge. This layer was not detected at station 12.

To estimate a yearly recharge rate the bromide recharge values were combined with the results from the water balance estimate of recharge. This was accomplished by scaling the results of the water balance estimation of recharge using the bromide data. The bromide tracer data provides a direct measurement of recharge whereas, as described in the previous section, the water balance method is empirical, which can result in an underestimation of recharge. In order to combine the data from both methods, the recharge estimated by the bromide traced from January 8 to May 7, 2008 was compared to the value estimated with the water balance method during the same period and a scaling factor was estimated. In order to accurately scale the water balance estimates of recharge, only tracer data from the stations that were not considered to have been affected by the ephemeral melt water streams were utilized. The average ratio of the bromide estimate for recharge compared to the water balance estimate of recharge was calculated using stations 2, 4, 6, 8, 10, 11, 12, 13 and 15. This resulted in an average Br : WB ratio estimation of recharge for the period of January 7 to May 7, 2008 of 1.5. This value of 1.5 was used as a factor to scale the water balance results for the previous May 2007 to January 2008 time period. As a comparison to verify the legitimacy of this scaling factor, the same approach was used on the 9 month bromide estimate of recharge and water balance estimate of recharge from Bekeris (2007). This resulted in a nearly identical average Br: WB of 1.6 for the period of July 2005 to May 2006. These results are displayed in Table 12.

Even considering the loss of bromide at several of the sites, the bromide tracer test remains the most robust recharge estimation method due its direct, physical measurement of the transportation of solutes within recharging groundwater. Both the centre and peaks of the bromide mass were simple to recognize. Considering the near surface geology, topography and potential for run-on/off and other local conditions, the bromide tracer method produced fairly sensible estimates of recharge. The main limitation associated with the bromide tracer test in this study was due to the short time allowed for tracer movement between coring episodes. It was necessary to develop a scaling approach to extrapolate four months of recharge estimated from the tracer test to a full year recharge rate using the results of the water balance method. The other drawback with using bromide to estimate recharge is that crops growth within the test area can be retarded which in turn reduces the amount of actual evapotranspiration due to lower leaf surface area, thereby artificially increasing the apparent recharge rate. However, this effect may be somewhat counteracted by the downward movement of the bromide tracer being slowed by recharging groundwater which is drawn back to the surface by roots.

4.9.3 Comparison of recharge estimates

Table 10 displays the results of the various recharge estimates made during time of this study and compares them to the best recharge estimate made by Bekeris (2007). Many factors affect recharge such as topography, near surface geology, precipitation, evapotranspiration and crop type. From station to station, topography and geology seem to most greatly affect recharge but from year to year it is the amount of precipitation, evapotranspiration and crop type that primarily affect recharge at a fixed location.

Due to the varying precipitation, crop types and methodologies utilized in estimating recharge at the site between this study and Bekeris (2007), it is difficult to directly compare recharge estimates. The May 2007 – May 2008 recharge estimate for station 3 is considerably lower than the previous estimate made by Bekeris (2007) but that is likely due to the ephemeral stream washing away most of the bromide tracer (only 4.7% was recovered in the core). Despite the low concentrations, the bromide concentrations relative to depth still provide a means of estimating the recharge at the locations that were influenced by ephemeral melt water streams. Overall, the earlier recharge estimates were generally a little lower in a slightly drier year, which suggests that the estimates of recharge at the eight stations are comparable. This lends credibility to the scaling factor method and would suggest that the yearly recharge values at all the stations are fairly accurate. The water balance method appears to underestimate recharge within a glacial terrain, especially during snow covered months and on a sub annual cycle.

Figure 42 features the contoured scaled, non-zero recharge estimates from May 2007 to May 2008 as listed in Table 10. The bromide test data generally correlate well with the original classifications based on topography and slope. It appears that the hydraulic conductivity of the near surface sediments is the most important factor in determining how much recharge occurs at a given location.

4.9.4 Neutron Probe Results

In order to relate the neutron probe count (CR) to a soil moisture content, CR measurements were converted to volumetric water content (θ_v) using the site specific calibration equation developed by Bekeris (2007). Neutron access tubes were installed during various drilling campaigns by the methods described in Section 3.1.2. The variations in θ_v with depth measured by the neutron probe at each of the recharge stations are presented in Figure 43, Figure 44 and Appendix H . Overall, each θ_v profile had a relatively consistent shape with depth and time. The degree of seasonal variability in the moisture content curves was different from site to site. Typically the highest moisture contents were measured in the spring when the snow was melting.

Station 2 (Figure 43) displayed very little seasonal variation, only about 3%. The marked decrease in moisture content at about 4 mbgs marks the aquitard/aquifer interface. Station 4 displayed a range throughout the year in volumetric moisture content of about 6%. The marked decrease in volumetric water content at about 3.2 mbgs reveals the aquitard/aquifer interface. Station 9 is located within the glacial outwash channel and along the path of an intermittent stream. It displayed the greatest range in moisture content throughout the year, as much as 20%. This is likely due to the highly permeable outwash sediments and high amount of recharge, especially during spring melt waters which also may have lead to flooding of the access tube. Station 10 (Figure 44) is comprised of fairly uniform sand. The exception is at about 3.5 mbgs where there is a thin, 25 cm layer of sandy silt. The neutron probe measurements reveal high moisture contents throughout the year at this layer suggesting that it may support a perched water table at this location. The neutron probe measurements at station 11 displayed remarkably little seasonal variability, typically ranging only about 2%. The moisture content remains fairly constant at about 23% except for a slight decrease at about 4 mbgs corresponding to a change in material from sandy silt to sandy clayey silt. Station 14 also showed a high degree of seasonal variability in measured moisture contents which ranged about 12%. This may in part be explained by its location within a gully and its fairly uniform, highly hydraulically conductive sandy materials.

The volumetric water content data from most of the soil cores from the November/December 2007 coring campaign generally matched well to the neutron probe measurements of soil moisture. Typically the soil cores measured slightly lower moisture content values than the neutron probe. This may be due to a small amount of moisture loss occurring between retrieval of the cores and the measurement in the lab as well as due to the larger averaging area for the neutron probe.

These detailed neutron probe measurements of moisture content provide greater insight into how the subsurface is affected by recharge events and fluctuating evapotranspiration rates on a seasonal basis, as opposed to yearly estimations provided by the bromide tracer study. This information can be utilized to evaluate how vulnerability may fluctuate temporally across the site.

4.10 Nutrient Management Practices

The cropping practices and amounts of nitrogen applied within each field in parcels A and B since 2002 are detailed in Table 13. Parcel B was subjected to BMP implementation since Oxford County purchased the land in 2003 and put it out for tender for the 2002/2003 growing season. This restricted nutrient application plan was developed by the Soil Research Group (SRG) in consultation with Oxford County personnel.

Table 14 displays the type of crop and amount of nitrogen applied in each of the fields from 2002 through 2008. The 112 kg/ha of N that is listed for 2002 in Parcel B was estimated by SRG (2006) using a computer model called NMAN that accounts for N cycling within an agricultural setting. Historically within the area, a combination of synthetic fertilizer and some manure was applied to a cropping practice of primarily corn, with some wheat and soybeans at about a 50-25-25 % area coverage respectively. The estimation assumed 150 lb/ac of N application for corn and calculated crop removal of 109 lb/ac leaving a surplus of 41 lb/ac. For wheat, NMAN estimated that of the assumed 100 lb/ac of N application, 90 lb/ac would be removed by crops leaving a surplus of 10 lb/ac. Soybeans do not require any N inputs. Therefore, the average amount of N applied to a given acre is 150*0.5 + 100*0.25 = 100 lb/ac and the amount of excess N in a given acre is 41*0.5 + 10*0.25 = 23 lb/ac surplus (SRG, 2006). The BMPs have switched to exclusive use of synthetic fertilizer applied to a 33-33-33 % rotation of corn-wheat-soy. Under this BMP, 87 lb/ac was applied for corn and 132 lb/ac was removed by crops leaving a deficit of 45 lb/ac. For wheat, 75 lb/ac was applied and 100 lb/ac was removed leaving a deficit of 25 lb/ac. Therefore, the average amount of N applied to a given acre is 87*0.33 + 75*0.33 = 54 lb/ac and the average shortfall of required N in a given acre is 45*0.33 + 25*0.33 = 25 lb/ac deficit (SRG, 2006). By looking at these pre-BMP and post-BMP crop rotations and N applications, it is clear that the 46% decrease in applied N within Parcel B represents a significant reduction in potential for N leaching as shown in Table 13. Despite the reduction in N application, crop yields since the BMP implementation have been at or above historical values (Don King, personal communication).

A comparison of Table 14 and Table 15 reveals the decrease in amount of nitrogen applied to the Parcel B fields compared to the suggested amounts. Since 2003, the fields planted in corn were applied an average of 42% of the average recommended nitrogen (194 lb/ac), with values ranging from 16 to 77% and decreasing from 2003 to 2008. The fields planted in winter wheat averaged 81%, with application rates ranging from 71 to 90% of the recommended values (100 lb/ac). Since 2003, only the soft variety of red winter wheat was planted due to its reduced need for nitrogen. The highly permeable sediments of the glacial outwash channel are located within Field 7 in Parcel B. In this field, no nitrogen has been applied since a small amount (9.7 kg N/ha) in April 2005. Grass has been allowed to grow in this field as well as field 3b in order to mine N from the shallow soil profile. Another method that has been utilized to reduce N application to the BMP activated fields was to plant N-fixing soybeans which do not require any fertilizer. Soybeans have been regularly planted in all eight fields since 2003 except for fields 3b (which has been in grass and N has not been applied) and field 2 and thus during these times these fields have not received N fertilizer. This detailed tracking of applied nutrient accurately documents exactly how the BMP was implemented across each field. These detailed measurements and the results of the study are very informative and can be utilized for planning and implementing BMPs in future studies.

4.11 Upscaling Evaluation

The ability to use information derived from discrete areas to predict what conditions may be like in other locations can be very useful. The data collected at each of the original eight stations have been analyzed and utilized in the creation of the new seven stations. The predictions that were made and updated as new information was collected gave insight into the relative significance of each criterion in the pursuit of successful upscaling. The main goals of the upscaling were to determine the conditions at locations outside of the study site at the time of the predictions. The condition that was of most interest was nitrate mass loading which could be determined by interpolating mass flux and recharge estimates at point locations where predictions had been made using the upscaling criteria.

The first stage of upscaling involved the selection of seven new stations, which were predicted to behave similarly to one of the original 8 stations. Choosing locations for these new stations was initially based on topography, with some consideration given to speculated near surface geology. However, because the site is characterized by near surface glacial moraine deposits, which can vary greatly in short distances, initially the prediction was primarily based on topography. With these predictions made, the new locations were selected and the coring and installation of neutron access tubes numbered AT20 through AT26 was completed at each new station (see Figure 8). After geologic coring had taken place and the near surface stratigraphy was analyzed, five of the initial 7 predictions were updated, illustrating that topography and speculated geology are not sufficient as predictive indicators. The final prediction used the results from the recharge estimates (see Section 4.9.2), which further altered one more prediction.

Table 7 displays the progression of how these predictions were updated as more information was collected and analyzed.

If the initial upscaling predictions were utilized to estimate nitrate mass loading using method 2 (see Section 4.14) the result would be 1.61 and 2.56 t/yr for Parcels A and B respectively for a total of 4.34 t/yr. This is very comparable to the 1.78 and 2.65 t/yr for a total of 4.26 t/yr that the final upscaling predictions estimated. However, it is believed that the near surface geology exerts the greatest control on how much water will recharge and thus the nitrate mass flux and loading. If a large area were predicted to have a very low hydraulic conductivity but in reality this was not the case, the resulting nitrate mass loading estimate would be significantly underestimated. It is recommended that the near surface geology be determined prior to scaling nitrate mass loading outside of the study site. Coring is suggested to be the most definitive tool to determine the near surface geology but referencing geologic maps may prove to be adequate in some circumstances. Secondary consideration should be given to areas that are located along the sides or bottom of steep hills as the potential for surface water to run-on/off is greatly increased. A topographic map or DEM should be incorporated into upscaling predictions as run-on/off will greatly affect the amount of recharge at these locations. It is further recommended that a GIS-based program be utilized to overlay weighting factors applied to each criterion which can be altered based on the topography and potential for run-on/off and as new geologic data are collected. These recommendations will greatly aid in developing modeling applications, which can be utilized to upscale point data to much larger areas.

4.12 Soil Nitrate Analytical Results

Field data collected from soil cores were preserved and analyzed as described in Section 3.3.6. Cores were sub-sampled in the lab and gravimetric and volumetric water content, bulk soil nitrate and porewater nitrate results were determined. Porewater nitrate plots at each station are found in Appendix I and an example is shown in Figure 45. These values were determined from the laboratory measured soil water content and the weighted average bulk soil nitrate concentration for each core. These plots display the relative nitrate concentration with depth and are typically highest near the surface within the root zone where biological activity is most prevalent. Appendix F displays the results of laboratory measured bulk soil nitrate and both the gravimetric and volumetric water content results for each of the stations. Appendix F also contains an in-depth description of these parameters at each station. Table 16 contains summarized depth-weighted porewater nitrate concentration and nitrate mass flux data for each of the stations.

Nitrate mass calculations excluded any samples above 1 mbgs due to the effect of N cycling within the root zone (see Section 3.3.6). Most of the highest bulk soil nitrate concentrations were measured within this upper 1 mbgs, with the highest measured value of 130 mg NO_3^--N/kg recorded at station 8. Typically, the average concentrations below 1 mbgs were 5 to 10 times lower than the peak concentrations measured above 1 mbgs. For example, the average depth-weighted bulk soil nitrate concentrations within a given core beneath the assigned root zone (1 mbgs) ranged from 0.1 mg NO_3^--N/kg to a high of 4.0 NO_3^--N/kg which was measured at station 8. Gravimetric moisture contents measured within the samples extracted from core samples varied greatly with sample composition, between 0.01 g/g in gravelly sand and 0.35 g/g in top soil. Porewater nitrate concentrations ranged from 0.1 mg NO_3^--N/L in sand to 228 mg NO_3^--N/L in the shallowest sample at station 14. Typical values below 1 mbgs ranged from 1 to 25 mg NO_3^--N/L. The average depth-weighted porewater nitrate concentrations within a given core beneath the assigned root zone (1 mbgs) ranged from 1.3 mg NO_3^--N/L to 46.2 mg NO_3^--N/L, which was measured at station 8.

4.13 BMP Effect on Unsaturated Zone Nitrate Concentration

At each of the original eight recharge stations established in 2005 within the field areas where nutrient applications had been decreased as part of the BMP activities and one site outside of this region (Station 7), replicate cores were collected within the unsaturated zone over the course of the current study to determine the cumulative amount of stored nitrate in the subsurface. The intention was to progressively monitor changes in the amount of stored nitrate as an indicator of any reductions in excess nitrate leaching past the root zone as a result of the BMP implementation. The results of the cumulative nitrate mass measurements at each of the initial 8 recharge stations are shown in Figure 46 through Figure 52. As Station 7 was not located on land that was subject to the BMP treatment, it is not considered here. The cumulative mass nitrate plots of station 7 and the seven new recharge stations, which only have 4 months of data, are shown in Appendix J.

For most of the recharge stations three consecutive years of coring done during the late spring are available for comparison. As can be seen in the figures, at each of the stations except Station 2, significant reductions in stored nitrate were documented within the shallow unsaturated zone. In order to compare at the same depth, the deepest sample point of the shallower of the two cores was chosen as the depth at which to make the comparison. If the deeper core did not have a sample at the same exact depth, the slope of the line connecting the point above and below was used to determine the cumulative mass at that chosen depth (see example in Figure 49). At stations 1, 2, 3, 4, 5, 6 and 8 the following decreases in the amount of cumulative nitrate were measured when comparing the most recent core with the core from 2 years earlier: 44, 37, 79, 60, 66, 29, and 66% respectively. Of particular note, Stations 3 and 6 show very large decreases in stored nitrate mass (if the March 2005 core is included for Station 6). These sites are characterized by sandy soils and Station 3 is located in topographically low area where significant vertical movement through the unsaturated zone would be anticipated. Station 2, situated at a topographically high point and underlain by a thick till unit, shows little overall decrease in stored nitrate over time although some minor annual variations are noted. Stations 4 is topographically higher than Stations 3 and 6, is characterized by lower permeability subsurface materials and shows a slightly less pronounced yet progressive decrease in stored nitrate over time. Tthe profiles at Station 1 show a high degree of variability over the annual cycles. Finally Station 8, where only grass has been grown over the last 3 years and no nutrients have been applied, shows very high overall cumulative mass values but a progressive decrease overall. This site is a former animal pasture; hence high bulk soil nitrate concentrations are likely a legacy of those past activities.

Overall, the long-term monitoring of the stored nitrate mass in the unsaturated zone beneath agricultural fields where BMPs are being applied show promise as a method for the early quantification of the performance of the BMPs, even in this highly complex hydrogeologic setting. In this particular case, the total stored mass of nitrate in the unsaturated zone throughout the Parcel B field area has decreased significantly. This indicates that the nutrient management practices that have been implemented are resulting in a reduction in the leaching of excess nitrate. Additional quantification of the total reductions realized over the course of the study is covered in the Section 4.14.

4.14 Quantification and Extrapolation of Nitrate Mass Flux

Four methods of extrapolating point measurements to nitrate mass loading measured at the recharge stations across each of Parcels A and B were tested and compared. The nitrate mass flux estimated at each station was based on average annual recharge and average porewater nitrate concentrations. The porewater nitrate, nitrate mass flux and recharge values utilized are listed in Table 16, with the summarized loading estimates for each method tabulated in Table 17. Nitrate mass flux maps for each of the four methods are found in Figure 53 through Figure 57. Porewater nitrate maps for each of the four methods as well as a table detailing how loading was calculated for each method are found in Appendix K and Appendix L respectively.

As described in Section 3.7, the Average method multiplied the average depth-weighted porewater nitrate concentration measured in Parcel A and B which was 6.71 and 7.60 mg NO_3-N/L (Appendix K) from the most recent cores collected at each of the fourteen stations by the average recharge measured at the corresponding stations which was 529 and 454 mm/yr respectively. This produced an average nitrate mass flux across the site of 3.93 and 3.44 g-N/m^2/yr (Figure 54). When multiplied by the area of each Parcel, the total nitrate mass loading beneath Parcel A was 1.74 t/yr and 2.55 t/yr beneath Parcel B for a total of 4.29 t/yr.

The Classification method attempted to subdivide both Parcel A and B into areas that are representative of one of the original 8 stations located within Parcel B (Figure 55). The porewater nitrate concentrations were multiplied by the corresponding station estimations of recharge to produce point nitrate mass flux values which were multiplied by the areas of the regions within the subdivided Parcels to produce total nitrate mass loading estimates of 1.61 and 2.65 t/yr beneath Parcels A and B respectively.

The Thiessen polygons method subdivided each Parcel (Figure 56). The area of each polygon was multiplied by the nitrate mass flux values associated with the station located within each polygon. This produced nitrate mass loading estimates of 1.81 and 2.26 t/yr for Parcels A and B respectively.

Lastly, the Contouring method estimated nitrate mass loading by contouring the nitrate mass flux values at each station. The average values between each contour interval were multiplied by the average recharge of the stations located within each Parcel and by the areas between each contour interval to produce nitrate mass loading estimates of 1.80 t/yr in Parcel A and 2.30 t/yr in Parcel B.

The average of the four methods of estimating nitrate mass loading value for Parcel A and B was 1.74 and 2.44 t/yr respectively. This is very close to method 1 (1.74 and 2.55 t/yr) in which a very simple average was taken of the fluxes at each station and multiplied by the area of each Parcel. Therefore, since the other three methods only varied by a maximum 11 % from method 1, method 1 was utilized to calculate mass loading values from the original 8 recharge stations in May 2006. These were calculated using nitrate mass flux estimates (Figure 53) multiplied by the area of Parcel B. The result was a nitrate mass loading of 6.77 t/yr beneath Parcel B. Comparing the 6.77 t/yr from May 2006 with the 2.55 t/yr from May 2008 results in a total mass reduction rate of 4.22 t/yr or 62 %. This reduction correlates fairly well with the 46% decrease in applied fertilizer within Parcel B (see Table 13). The amount of nitrate mass that has been extracted from the supply wells from May 2007 to May 2008 was 22 tonnes, as shown in Table 18. If the 4.22 t/yr reduction in the porewater nitrate is applied to the 22.0 t/yr extracted from supply wells 1, 3, 5, 8 and 11, the average nitrate concentration in the supply wells would decrease 19 % from 7.8 to 6.3 mg NO_3-N/L.

4.15 Vulnerability Assessment Results

This section will compare the results of the AVI, ISI and SAAT vulnerability assessments that were completed within the capture zone of the Thornton Well Field. AVI and ISI are indexing methods that produce dimensionless results whereas the SAAT method ranks vulnerability in terms of years for contaminants to travel from the surface to the water table. These methods, which are utilized to calculate the vulnerability rankings, are described in Section 3.8. The results for each location of all three assessments are listed in Table 19. Of the 42 locations that had stratigraphic logs available for use in the calculations, only 9 were ranked in the same category by each of the methods. However, there is no extremely high category for AVI assessment. If all the extremely high rankings for the AVI approach were categorized as having high vulnerability, then 21 of the 42 locations would have the same ranking based on the different approaches.

4.15.1 AVI

The AVI method ranks vulnerability by taking the quotients of each geologic stratum's thickness and K-factor which are summed down to the depth of the calculated average yearly water table. The K-value represents the amount of protection offered by a stratum and is generally related to the negative exponent of the vertical hydraulic conductivity of the layer. The results of the AVI assessment are shown in Figure 58. Vulnerability at the site ranked in the extremely high, high and moderately vulnerable categories. Vulnerability tended to decrease northwestward, which generally correlates with increasing depth to the water table. The most vulnerable areas were in the woodlot, throughout the glacial outwash channel and the deep, sandy gulley that runs northwest-southeast through Parcel A. The least vulnerable areas were high in elevation, especially near the meteorological station and in the northwestern area of the study site.

One issue that may be seen as problematic is the subjective nature of the selection of the vulnerability categories. In order for a location to be considered to have “low vulnerability”, the sum of the hydraulic resistances for all the layers need to fall in the range of 1000 to 10000. Because the values are summed, without having at least one layer that has a value in that range (a clay unit), it would be necessary to have numerous layers (an extremely thick unsaturated zone) to be able to reach such a high sum. At this study site, there are areas that have very thick unsaturated zones but nowhere are these thick unsaturated zones only comprised of very fine grained (high hydraulic resistance) layers. Thus, no areas qualify as being categorized as having “low vulnerability”. Perhaps the relative geologic context of the study should define the subjective range of the vulnerability categories.

4.15.2 ISI

This method is similar to the AVI method in that each geologic layer is assigned a factor based on primary sediment composition type (ranging from 2 to 8) that is simply multiplied by the thickness of that layer. The main difference between the ISI and AVI methods is that in order to apply the ISI method, the target aquifer must first be labeled as confined or unconfined (see Section 3.8.2). All three ISI vulnerability categories were found across the study site, as depicted in Figure 59. The majority of the woodlot and outwash channel is ranked as highly vulnerable whereas the gulley is moderately vulnerable. However, overall, the vulnerability patterns were similar to that of the AVI approach. A major difference is the categorization of the vulnerability in the areas with thick unsaturated zones. In these regions, layers of fine sediments are more commonly found between the surface and the water table. Compared to the AVI approach, the ISI method places more significance on these layers in terms of potential to reduce vulnerability. WO68 was categorized as low vulnerability whereas the AVI approach categorized it as being extremely high. Nine other locations with thick unsaturated zones have ISI rankings that are two categories less vulnerable than the AVI ranking.

4.15.3 SAAT

The SAAT vulnerability assessment is slightly different from the AVI and ISI because it produces results in time instead of a numerical index. It requires a recharge value as an input. Fields where SAAT calculations were completed used the summed non-zero monthly surplus water balance recharge value for the corresponding field. SAAT locations where no water balance calculations were completed, the average of the summed non-zero monthly surplus recharge value for all the fields was applied. This average value of 0.456 m/yr was significantly lower than 0.645 m/yr which was the average of the values estimated using the combined water balance/bromide tracer approach (see Section 3.4.2.3). Therefore, the SAAT estimation may be underestimated for the year 2008 since it was such a wet year, but it is considered to be fairly representative of the long-term vulnerability at the site.

The study site was split fairly evenly between highly and moderately vulnerable locations. Figure 60 shows the same general pattern of vulnerability decreasing northwestward, which correlates well with the AVI and ISI approach. Of the 42 locations that were calculated using the SAAT approach, 31 were ranked in the same category as the ISI approach and 12 were the same as the AVI approach (32 if the “extremely high” category were removed from the AVI ranking system and counted as “high”). The average travel time from surface to the top of the water table was 4.3 years and ranged from 0.3 to 13.0 years. All eight well locations that had travel times less than one year were found at the supply wells or within the woodlot except at station 1.

4.15.4 Summary of Vulnerability Assessment Techniques

The AVI, ISI and SAAT are well established, commonly applied methods of assessing the vulnerability of an aquifer system from surface contaminants. AVI and ISI are indexing methods that do not utilize physically measured temporal data from the target of the vulnerability investigation. The SAAT approach does not utilize numerical factors like the AVI and ISI approaches but instead relies on the hydraulic conductivity of the overlying geologic strata to assess the protection these layers offer to the water table from surface contaminants. The SAAT approach produces a more tangible result, which is measured in years. This approach is fairly simple to apply and the intuitive nature of the results makes it the recommended technique to employ.

These standardized methods of evaluating vulnerability lack direct, quantified evidence of the conditions in the field. Since many physical conditions at a site do not remain constant with time, monitoring key field parameters can aid in the evaluation of how vulnerability may be temporally affected by these changing conditions. Air temperature, groundwater temperature and hydraulic head are parameters that can be monitored to determine when and if selected locations across the site are more vulnerable to surface contaminants (as discussed in Section 4.6.2.4). These parameters can also be utilized to verify results obtained from the standardized methods of assessing vulnerability.

4.15.5 Comparison of Vulnerability Rankings to Pressure and Temperature Responses

The AVI, ISI and SAAT assessments each yielded similar but slightly different aquifer vulnerability results (Table 19). These results were then compared to the responses of the pressure and temperature in the monitoring wells as an independent assessment of the vulnerability of the aquifer. The "fast" responding locations (Section 4.6.2.1) can be considered highly vulnerable to contamination, whereas the "moderate" (Section 4.6.2.2) and "slow" (Section 4.6.2.3) responding wells can be considered of moderate and low vulnerability respectively.

The contoured AVI values (Figure 58) identify areas that range from extremely vulnerable to moderately vulnerable. There are no areas on the map that were calculated to be of low vulnerability. The AVI method does a reasonably good job of identifying vulnerable areas such as in the outwash channel where the "fast" responding stations 1, 6 and 9 are ranked as extremely highly vulnerable. However, the areas that were identified as having a slow response to temperature and pressure the AVI method calculated to be highly vulnerable. In a general sense, the AVI map of vulnerability identifies the highly vulnerable areas and shows a good relative sense of vulnerability between locations but there are many areas such as at stations 2 or 12 and 13 that are inaccurately ranked as too high in vulnerability when compared to temperature and pressure data. A possible solution may be to slightly adjust the intervals, which divide AVI vulnerability ranking categories to better define lower vulnerability conditions.

The contoured ISI values (Figure 59) identify areas that range from high to low vulnerability. The ISI method is quite capable of identifying the highly vulnerable outwash channel and the low vulnerability associated with the low permeable sediments of the thick unsaturated zone at WO76 (near stations 12 and 13) and WO61 (station 2). The "fast" responding areas were ranked high in ISI vulnerability, the "moderate" areas as moderate in ISI vulnerability. The "slow" responding station 2 was ranked as low vulnerability whereas the cores taken at stations 12 and 13 were ranked as moderate. These cores however were not nearly deep enough to reach the water table, so the geology at depth was inferred. The monitoring well (WO76) in between these two stations was installed to a much greater depth and the geology used for the ISI calculation ranked it as being of low vulnerability. This example highlights the importance of having an accurate representation of geology and how the response of well WO76 was consistent with the geology.

The contoured SAAT values (Figure 60) indentify areas that range from high to moderate vulnerability. Like the AVI and ISI methods, the SAAT approach clearly identifies the highly vulnerable glacial outwash channel and the "fast" responding wells were ranked likewise. Each of the "moderate" responding areas were also ranked as moderately vulnerable. However, the "slow" responding stations 2, 12 and 13 were ranked as moderate in vulnerability.

Overall, the transient hydrological conditions at a site are the most critical element in estimating travel times and thus assessing vulnerability. The recharge component of the SAAT technique is the only method that begins to account for hydrological conditions. For this study, the ISI method produced results that most closely approximated the responses to temperature and pressure but in general the SAAT vulnerability assessment technique provided the most physically comprehensive results.

Table 4. Details of new monitoring well installations

Well Name	Screened interval (mbgs)[1]	Material at well screen	Aquifer number screened in[3]	Depth to water[2] (mbgs)	Total depth of boring (m)
WO67	15.24-18.29	sand, silt, gravel	2	12.94	36.58
WO68	36.42-39.47	sand	3	33.36	41.51
WO69	25.91-28.96	sand	3	25.24	32.00
WO70	25.83-281.9	sand, gravel	3	26.80	35.05
WO71-S	9.14-10.36	silt, sand	3	2.02	10.67
WO71-D	16.76-20.42	sand, gravel	3	2.50	22.86
WO72-S	13.41-16.40	gravel, sand	2	11.03	16.46
WO72-D	17.87-20.67	gravel, sand	2	10.98	28.96
WO73-S	13.41-16.46	sand, gravel	2	n/a	16.46
WO73-D	22.10-25.86	sand, gravel	2	18.33	38.10
WO74-WT	3.05-5.94	gravel, sand, silt	2	3.66	6.10
WO74-S	9.14-10.36	silt, sand	2	3.66	10.67
WO74-M	12.50-13.72	sand, gravel	2	3.65	14.02
WO74-D	14.94-17.98	gravel	2	3.64	21.34
WO75-S	8.84-10.36	sand, gravel	2	5.57	10.67
WO75-D	18.29-21.34	sand	2	5.57	24.38
WO76	35.05-38.10	sand	3	30.47	42.67

Notes:

[1] meters below ground surface.

[2] depth to water measured at time of individual slug testing (dates listed at top of each well log in Appendix B)

[3] aquifer number refers to an aquifer naming scheme described by Haslauer (2005).

Table 5. Survey data

Well	Easting	Northing	Well	Easting	Northing
WO02	520295.2389	4770103.923	WO61	519584.0837	4770113.481
WO04-D	520114.3877	4770381.168	WO62	519920.7353	4770427.858
WO06	520294.972	4769918.848	WO63	519848.4703	4770360.172
WO07	520228.5138	4770182.583	WO64	519882.2452	4770192.991
WO08	520296.29	4770261.536	WO65	519577.3934	4770550.061
WO09	520341.806	4770288.501	WO66	519682.8523	4770485.676
WO11	519655.5396	4770438.1	WO67	519488.27	4770318.11
WO12	520126.549	4769499.307	WO68	519231.13	4770032.89
WO18	520456.41	4769881.85	WO69	518627.5	4769467.58
WO19	520344.0762	4769265.969	WO70	518180.75	4769744.76
WO20	520317.266	4769283.764	WO71-D	519049.97	4770550.17
WO22	520254.544	4769779.156	WO72-D	519790.61	4770579.85
WO24	519035.3393	4770557.909	WO73-D	519937.07	4770754.01
WO27	520409.6984	4770090.35	WO74-D	520056.14	4770155.97
WO28	518992.9361	4769792.185	WO75-D	520013.59	4770112.04
WO28-D	518990.4364	4769791.472	WO76	519338.21	4769424.85
WO29	519232.5107	4770032.132	Station 10	519702.342	4769229.421
WO30	519427.1229	4770223.649	Station 11	519997.275	4768758.287
WO31	519926.8407	4769695.319	Station 12	519341.589	4769430.341
WO32	519504.9894	4770299.355	Station 13	519332.911	4769424.708
WO33	519736.9869	4770244.366	Station 14	519230.673	4769025.512
WO35	519976.3325	4770191.93	Station 15	518880.496	4769198.166
WO36	520060.4564	4770310.281	Supply well 1	520437.886	4770137.36
WO37	519847.471	4770360.903	Supply well 11	519014.786	4768709.36
WO40	519546.7728	4770561.811	Supply well 3	520344.886	4769918.36
WO56	519758.4666	4769720.313	Supply well 5	520444.886	4770102.36
WO58	519343.9532	4769789.942	Supply well 8	520223.886	4769546.36
WO60	519406.1871	4769960.682			

Table 6. Results of nitrate isotopic analysis

Well	Date	^{15}N	Repeat ^{15}N	^{18}O	Repeat ^{18}O
		‰	‰	‰	‰
WO72-S	Aug1/07	5.55	5.25	2.43	
WO69	Aug1/07	6.01		1.02	
WO62	Aug1/07	5.75		0.27	
WO11-6	Aug29/07	5.22	5.41	-0.29	
WO11-8	Aug29/07	6.13		0.24	
WO11-13	Aug29/07	6.76		1.13	
WO71-S	Aug29/07	9.56		2.21	
WO71-D	Aug29/07	6.60	6.63	1.64	1.11
WO70	Aug29/07	5.78		1.11	
WO73-D	Aug29/07	7.24		2.60	
WO61	Aug30/07	5.26		3.13	2.94
WO76	Aug30/07	6.74		1.47	
WO60	Aug30/07	7.09	7.31	1.81	
WO09-10	Aug30/07	5.15		not enough	
Supply Well 1	Aug30/07	6.09		2.68	
Supply Well 5	Aug30/07	6.37		1.73	
WO40	Aug29/07	6.10		0.38	
WO63	Aug1/07	6.83	6.78	0.98	
WO74-S	Sep-07	6.35		0.30	1.35
WO74-D	Sep-07	6.30		1.68	

Table 7. Characterization of recharge stations and progression of predictions for new recharge stations

Station	Field	Topography	Near Surface Geology	Recharge (May 07-May 08)	Initial Prediction	Secondary Prediction	Final Prediction
	Parcel B: 7			(mm/yr)	(Topography)	(Geology, Topography)	(Geology, Topography, Recharge)
1	Parcel B: 4	low, flat	sand & gravel	507			
2	Parcel B: 3a	high, flat	silt till	417			
3	Parcel B: 5	low, flat	silt & sand	400			
4	Parcel B: 3b	slope	silt till	471			
5	Parcel B: 7	low, flat	sand & silt	522			
6	Old Stage Rd.	slope	sand & gravel	393			
8	Parcel B: 6	low, flat	silt till	522			
9	Parcel B: 7	Low, flat	sand and gravel	477	1	1	1
10	Parcel B: 1	minor slope	sand	508	4	6	6
11	Parcel B: 1	low, flat	sand and silt	383	3	4	2
12	Parcel B: 2	high, flat	sand and gravel	375	2	1	1
13	Parcel A: 3	high, flat	sand and gravel	601	2	1	1
14	Parcel A: 1	low, slope	sand	662	4	3	3
15	Parcel A: 1	slope	sand	491	6	6	6

Table 8. Water balance recharge estimates for 2007 (January 1 to December 31)

Year	Station	Crop	Precipitation (mm/yr)	Evapotranspiration (mm/yr)	Recharge (mm/yr)
2007	1	grass	835	969	-134
2007	2	winter wheat	835	774	61
2007	3	grass	835	969	-134
2007	4	winter wheat	835	774	61
2007	5	grass	835	969	-134
2007	6	grass	835	969	-134
2007	8	grass	835	969	-134
2007	9	grass	835	969	-134
2007	10	corn	835	719	116
2007	11	corn	835	719	116
2007	12	r. beans/w. wheat	835	790	45
2007	13	corn	835	719	116
2007	14	corn	835	719	116
2007	15	corn	835	719	116

Table 9. Water balance recharge estimates for 2008 (January 1 to October 31)

Year	Station	Crop	Precipitation (mm)	Evapotranspiration (mm)	Recharge (mm)	Recharge* (mm/yr)
2008	1	grass	1082	887	195	315
2008	2	corn	1082	722	360	480
2008	3	grass	1082	887	195	315
2008	4	corn	1082	722	360	480
2008	5	grass	1082	887	195	315
2008	6	grass	1082	887	195	315
2008	8	grass	1082	887	195	315
2008	9	grass	1082	887	195	315
2008	10	soy beans/w. wheat	1082	839	243	363
2008	11	soy beans/w. wheat	1082	839	243	363
2008	12	winter wheat	1082	874	208	328
2008	13	corn	1082	853	229	349
2008	14	soy beans/w. wheat	1082	839	243	363
2008	15	soy beans/w. wheat	1082	839	243	363

*Surplus recharge values for the months of November and December were estimated at 80 and 40 mm respectively

Table 10. Recharge estimate comparison

Station	Recharge* May05-May06 (mm/yr)	Unscaled, non-zero WB + Br May07-May08 (mm/yr)	Scaled WB + Br May07-May08 (mm/yr)	Precipitation May05-May06 (mm)	Precipitation May07-May08 (mm)
1	430	423	507	802	980
2	210	314	417	802	980
3	590	316	400	802	980
4	520	368	471	802	980
5	510	348**	522**	802	980
6	430	309	393	802	980
7	640	335**	522**	802	980
8	270	348**	522**	802	980

*(Bekeris, 2007)

**Based on water balance only

Table 11. Bromide tracer data and recharge estimates

Station	Recovered Br (kg)	% of applied Br	Centre of Mass (mbgs)	Recharge Br method Jan 8 ~ May 7 2008 (mm)
1	0.09	2.5	1.52	337
2	0.7	19.3	0.46	135
3	0.17	4.7	1.32	274
4	2.47	67.8	0.67	176
6	2.75	75.4	0.77	150
9	0.55	15.2	1.38	285
10	1.78	48.7	1.08	203
11	0.65	17.9	0.31	94
12	4.45	122.1	0.77	152
13	1.68	46.1	1.60	395
14	2.97	81.6	1.28	335
15	2.26	62	0.73	199

Table 12. Recharge estimate comparison for determination of scaling factor

Station	Bekeris Bromide July 05 - May 06 (mm)	Bekeris Water Balance July 05 - May 06 (mm)	Br:WB	Koch Bromide January - May 08 (mm)	Koch Water Balance January - May 08 (mm)	Br:WB
1	430	205	2.1	337	106	3.2
2	210	235	0.9*	135	107	1.3*
3	590	205	2.9	274	106	2.6
4	520	235	2.2*	176	107	1.6*
5	510	173	2.9		106	
6	430	205	2.1*	150	106	1.4*
7	640	231	2.8			
8	270	235	1.1*		106	
9				285	106	2.7
10				203	147	1.4*
11				94	147	0.6*
12				152	101	1.5*
13				395	151	2.6*
14				335	147	2.3
15				199	147	1.4*
Average			**1.6***			**1.5***

* Stations that were not affected by spring melt water streams

Table 13: Changes in nutrient loading within Parcel B.

	Historical Practice	Modified Practice
Crops	Cattle/Hog production; primarily corn cropping, some wheat and soy	Soy-wheat-corn rotation; some fields in permanent grass
Applied Nutrients	Synthetic fertilizer, some manure	Synthetic fertilizer
Average N application	100 lb/ac	54 lb/ac
N - Balance	(+) 23 lb/ac	(-) 25 lb/ac

Table 14. Recent crop and nitrogen application history at study site.

	2002		2003		2004		2005		2006		2007		2008	
Field	Crop	Applied nitrogen, kg N/ha (month)	Crop	Applied nitrogen, kg N/ha (month)	Crop	Applied nitrogen, kg N/ha (month)	Crop	Applied nitrogen, kg N/ha (month)	Crop	Applied nitrogen, kg N/ha (month)	Crop	Applied nitrogen, kg N/ha (month)	Crop	Applied nitrogen, kg N/ha (month)
Parcel A														
1			Corn	78 (May) 60 (June)	Corn	90 (June)	Corn	91 (May) 60 (June)	Corn	91 (May) n/a (June)	Corn	unknown	Corn	112 (June)
2			Corn	78 (May) 60 (June)	Corn	90 (June)	Corn	91 (May) 60 (June)	Corn	n/a (June)	Corn	unknown	Soybeans	0
3			Corn	90 (June)	Corn	78 (May) 60 (June)	Corn	90 (June)	Corn	91 (May) n/a (June)	Corn	unknown	Soybeans	0
Parcel B														
1	Corn	112*	Soybean	0	Corn	12 (May) 96 (June)	Soybean	0	Winter wheat	90 (April)	Corn	unknown	Soybean	unknown
2	Corn	112*	Corn	20 (May) 114 (June)	Romano beans	19 (May) 5 (July)	Winter wheat	3.6 (Oct.) 82 (April)	Corn	26 (May) 50 (June)	Romano beans	unknown	Winter wheat	unknown
3a	Corn	112*	Soybean	0	Winter wheat	5.5 (Oct.) 65 (May)	Oats/grass	9.7 (April)	Soybeans	0	Soybeans	0	Winter wheat Red Clover	90 (April)
3b	Corn	112*	Grass	0	Grass	0	Grass	0	Grass	0	Grass	0	Grass	0
4	Corn	112*	Soybean	0	Winter wheat/ Clover	5.5 (Oct.) 65 (May)	Corn	27 (May) 62 (June)	Romano beans Winter wheat	26 (June)	Winter wheat Red Clover	90 (April)	Corn	50 (June)
5	Corn	112*	Soybean	0	Winter wheat/ Clover	5.5 (Oct.) 65 (May)	Corn	27 (May) 53 (June)	Soybean Winter wheat	0	Winter wheat/ Red Clover	90 (April)	Corn	50 (June)
6	Corn	112*	Soybean	0	Winter wheat/ Clover	5.5 (Oct.) 65 (May)	Corn	27 (May)	Soybean Winter wheat	0	Winter wheat/ Red Clover	90 (April)	Corn	45 (June)
7	Corn	112*	Soybean	0	Winter wheat/ Clover	5.5 (Oct.) 65 (May)	Oats/grass	9.7 (April)	Grass	0	Grass	0	Grass	0
Old Stage Road	Alfalfa	0*	Alfalfa	n/a	Corn	n/a	Soybean	n/a	Winter Wheat	n/a	Corn	n/a	Corn	n/a

*Estimated by the Soil Research Group (2006).

Table 15. Recommended and assumed yearly nitrogen application rates estimated by Soil Research Group (2006)

Crop	Typical Nitrogen Application (kg N/ha)	Notes
Corn	157 – 190 annual total	May be decreased by planting red clover with wheat in the preceding year
Hard red winter wheat	157 – 168 134 (minimum)	Crop's value depends upon protein content
Soft red winter wheat	100	Low protein content is ideal
Soybean	0	Nitrogen fixer, no need for N application

Table 16. Data used for upscaling to nitrate mass loading

Station	Distance Weighted Average Porewater Nitrate Concentrations May 2006 (mg-N/L)	Recharge May 2005-May 2006 (m/yr)	Mass Flux May 2005-May 2006 (g NO_3-$N/m^2/yr$)	Distance Weighted Average Porewater Nitrate Concentrations May 2008 (mg NO_3-N/L)	Recharge May 2007-May 2008 (m/yr)	Mass Flux May 2007-May2008 (g NO_3-$N/m^2/yr$)
1	13.13	0.43	5.65	6.39	0.507	3.24
2	21.23	0.21	4.46	8.87	0.417	3.70
3	5.77	0.59	3.41	3.11	0.400	1.24
4	19.89	0.52	10.34	7.89	0.471	3.71
5	8.79	0.51	4.48	2.68	0.522	1.40
6	12.22	0.43	5.25	11.20	0.522	4.40
8	69.85	0.27	18.86	19.80	0.522	10.34
9				3.10	0.477	1.48
10				1.32	0.508	0.67
11				13.76	0.383	5.27
12				5.52	0.375	2.07
13				3.47	0.601	2.09
14				10.50	0.662	6.95
15				6.17	0.491	3.03
Parcel B Average	21.55	0.42	7.49	7.60	0.46	3.41

Table 17. Summary of extrapolated nitrate mass loading results.

Method	Parcel	Nitrate Mass Loading (t/yr)
1	A	1.74
	B	2.55
2	A	1.61
	B	2.65
3	A	1.81
	B	2.26
4	A	1.80
	B	2.30

Table 18. Pumping rates, average nitrate concentrations and mass of nitrate extracted from supply wells in the Thornton Well Field from May 2007 to May 2008.

	Pumping Rate May 2007-May 2008 (m^3/yr)	Yearly Average Nitrate Concentration (mg NO_3-N/yr)	Yearly Extracted Mass (t/yr)
Well 1	692781	8.9	6.1
Well 3	281952	8.5	2.4
Well 5	85976	7.7	0.7
Well 8	716993	7.5	5.4
Well 11	1131966	6.5	7.4
Total	2909668	7.8	22

Table 19. Results of vulnerability assessments

Well	AVI	Ranking	ISI	Ranking	SAAT (years)	Ranking	Temp/ Pressure
WO02	0.823	Extremely High	20.441	High	2.24	High	
WO04-D	-3.893	Extremely High	16.827	High	1.95	High	
WO06	-3.156	Extremely High	11.550	High	1.67	High	
WO07	-4.117	Extremely High	7.230	High	1.32	High	
WO08	-4.995	Extremely High	6.380	High	0.70	High	
WO09	1.550	High	8.960	High	0.98	High	
WO11	0.985	Extremely High	37.562	Moderate	4.21	High	High
WO22	-1.170	Extremely High	13.460	High	1.48	High	
WO35	1.945	High	30.112	Moderate	0.69	High	Moderate
WO36	1.756	High	15.937	High	1.85	High	
WO37	1.154	High	8.064	High	0.94	High	
WO40	0.780	Extremely High	23.442	High	2.87	High	High
WO56	1.035	High	43.572	Moderate	5.67	Moderate	Moderate
WO58	1.079	High	61.675	Moderate	8.35	Moderate	
WO60	1.917	High	91.185	Low	8.45	Moderate	Low
WO61	2.301	Moderate	64.624	Moderate	5.63	Moderate	Moderate
WO62	-1.017	Extremely High	20.960	High	2.97	High	High
WO63	-3.499	Extremely High	6.682	High	0.45	High	High
WO64	1.202	High	32.247	Moderate	4.16	High	Moderate
WO65	1.202	High	15.958	High	1.87	High	
WO66	1.145	High	19.516	High	2.13	High	High
WO67	2.004	Moderate	58.532	Moderate	6.81	Moderate	
WO68	0.852	Extremely High	88.680	Low	11.57	Moderate	
WO69	0.937	Extremely High	74.276	Moderate	9.90	Moderate	
WO70	2.094	Moderate	117.320	Low	12.97	Moderate	
WO71-D	2.231	Moderate	58.500	Moderate	6.55	Moderate	
WO72-D	1.001	High	52.820	Moderate	6.24	Moderate	
WO73-D	2.017	Moderate	80.202	Low	9.39	Moderate	
WO74-D	-0.079	Extremely High	13.688	High	1.43	High	
WO75-D	-2.937	Extremely High	17.994	High	1.68	High	
WO76	1.349	High	96.000	Low	10.88	Moderate	Low
Station 10	-2.193	Extremely High	40.900	Moderate	4.64	High	
Station 11	-2.349	Extremely High	17.700	High	1.57	High	
Station 12	-3.526	Extremely High	61.500	Moderate	9.13	Moderate	Low
Station 13	0.502	Extremely High	62.900	Moderate	7.45	Moderate	Low
Station 14	-1.796	Extremely High	45.700	Moderate	5.09	Moderate	
Station 15	-3.532	Extremely High	55.900	Moderate	6.27	Moderate	
Supply well 1	-5.329	Extremely High	2.960	High	0.33	High	
Supply well 3	1.761	High	21.243	High	2.33	High	
Supply well 5	-1.134	Extremely High	5.510	High	0.89	High	
Supply well 8	-5.244	Extremely High	8.072	High	0.40	High	
Supply well 11	1.832	High	40.920	Moderate	5.93	Moderate	

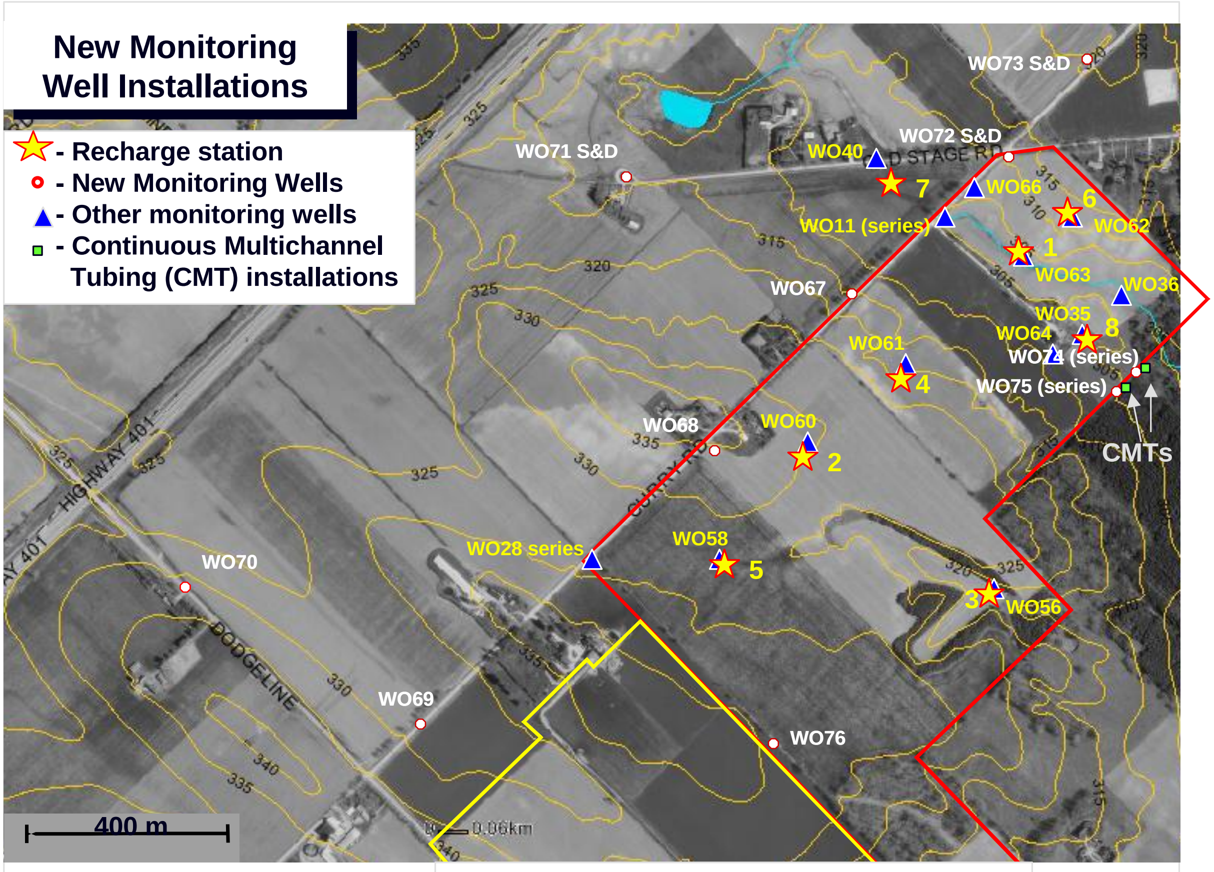


Figure 11. Location of recharge stations 1 to 8 existing prior to the start of this project (numbered red/yellow stars), new monitoring wells (white solid circles), CMT installations (green squares), and partial listing of existing monitoring wells (blue triangles).

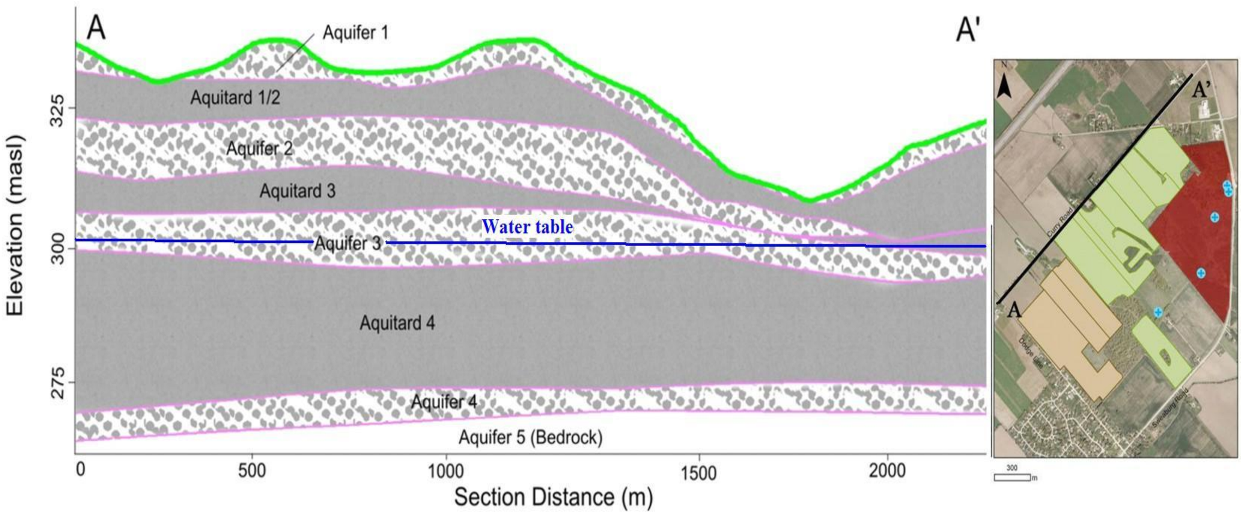


Figure 12. Cross Section A-A' along Curry road.

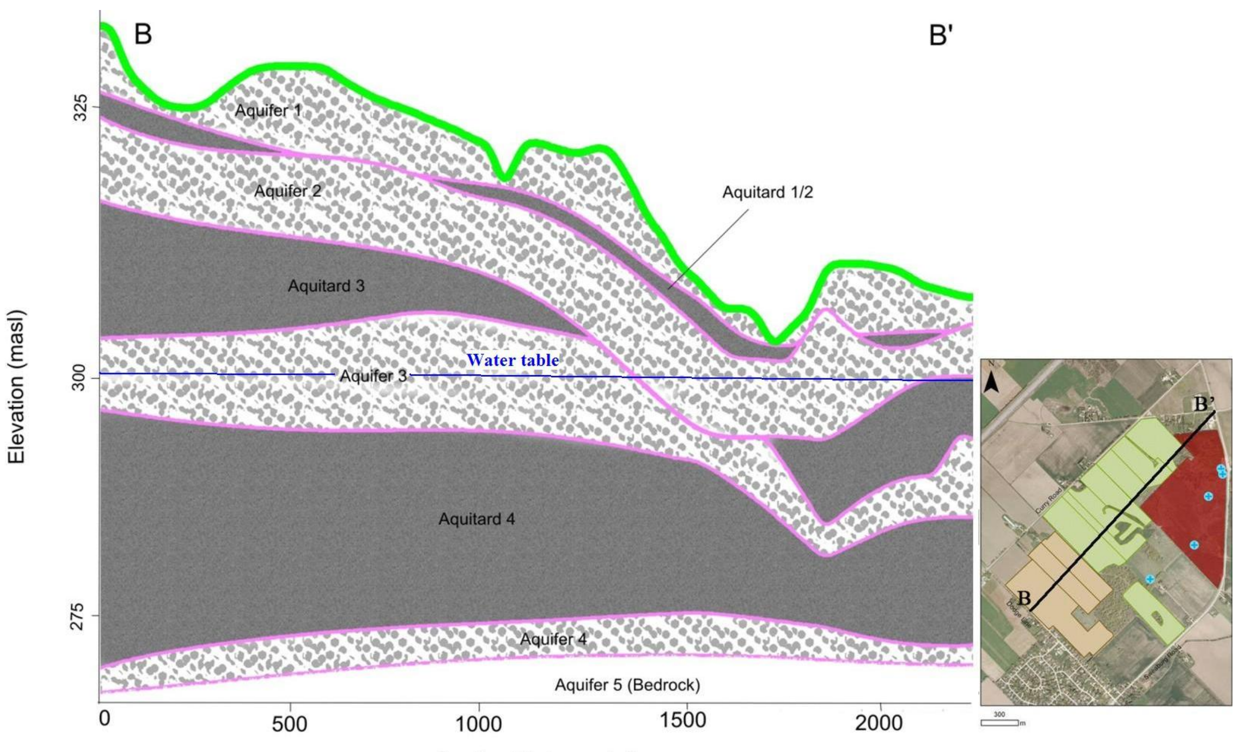


Figure 13. Cross section B-B' parallel to Curry road, approximately 500 m to the southeast.

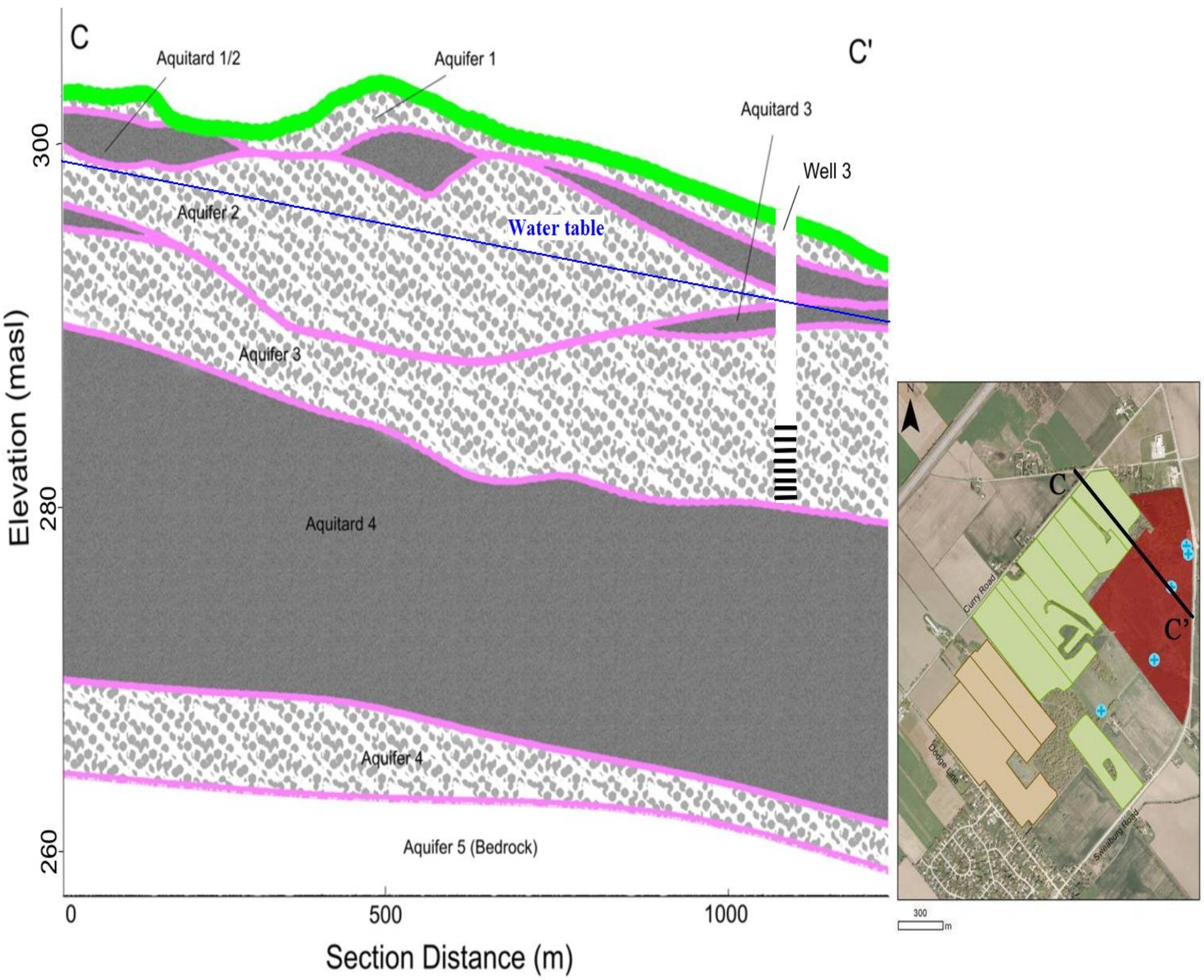


Figure 14. Cross section C-C' through glacial outwash channel and woodlot.

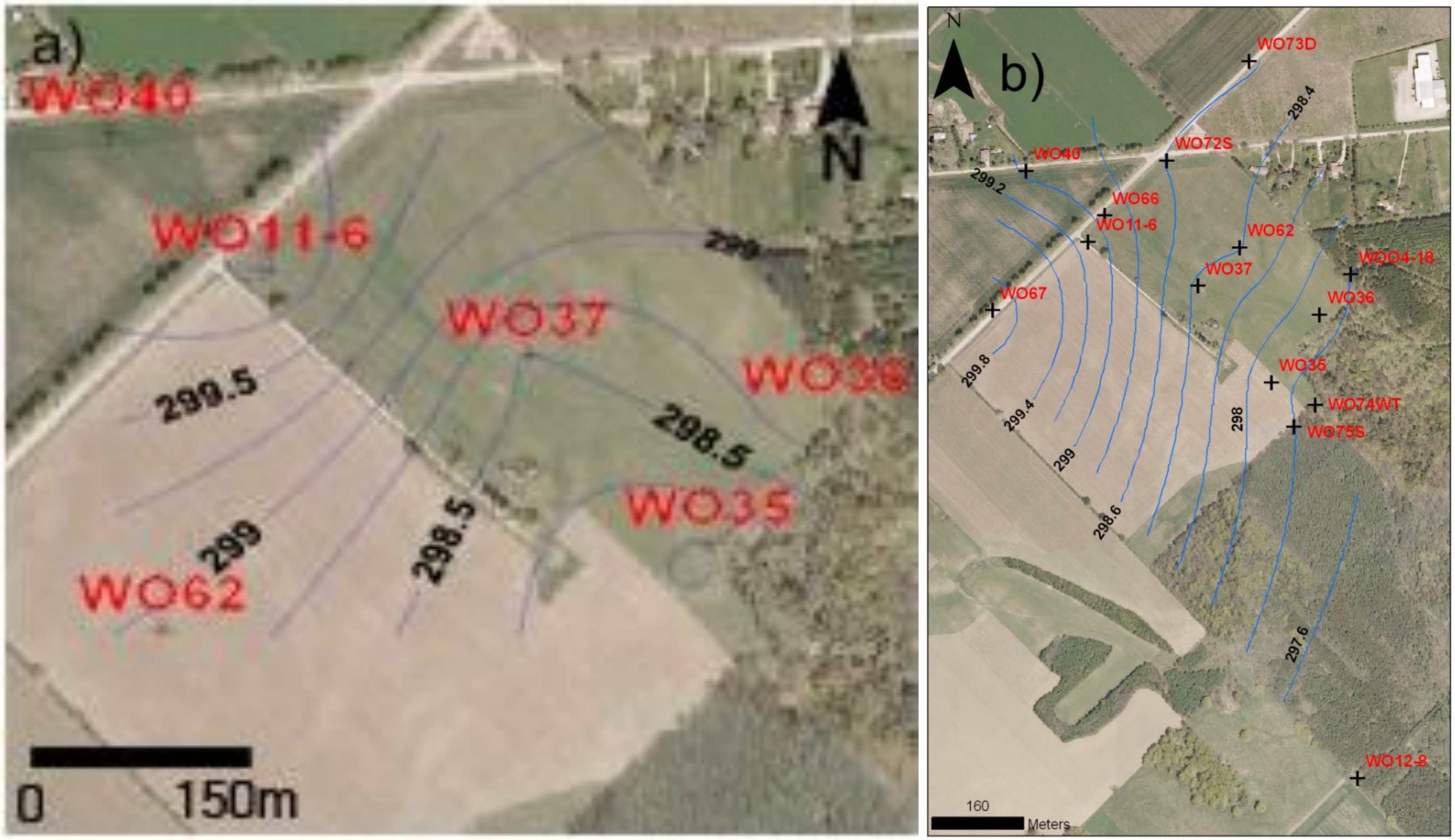


Figure 15. Hydraulic head contour maps estimated from pressure data collected from Aquifer 2 wells. Data displayed was collected a) January 8, 2007 and b) May 21 & 22, 2008.

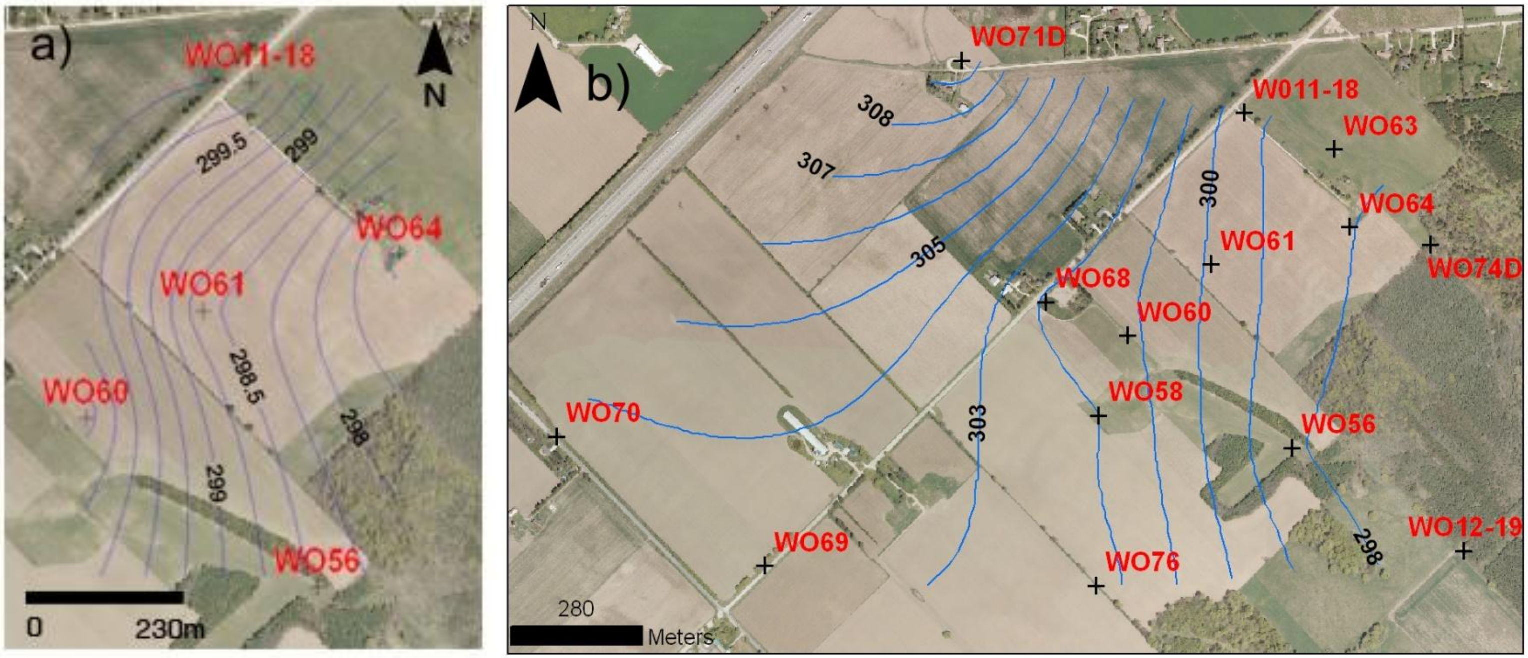


Figure 16. Hydraulic head contour maps estimated from pressure data collected from Aquifer 3 wells. Data displayed was collected a) January 8, 2007 and b) May 21 & 22, 2008.

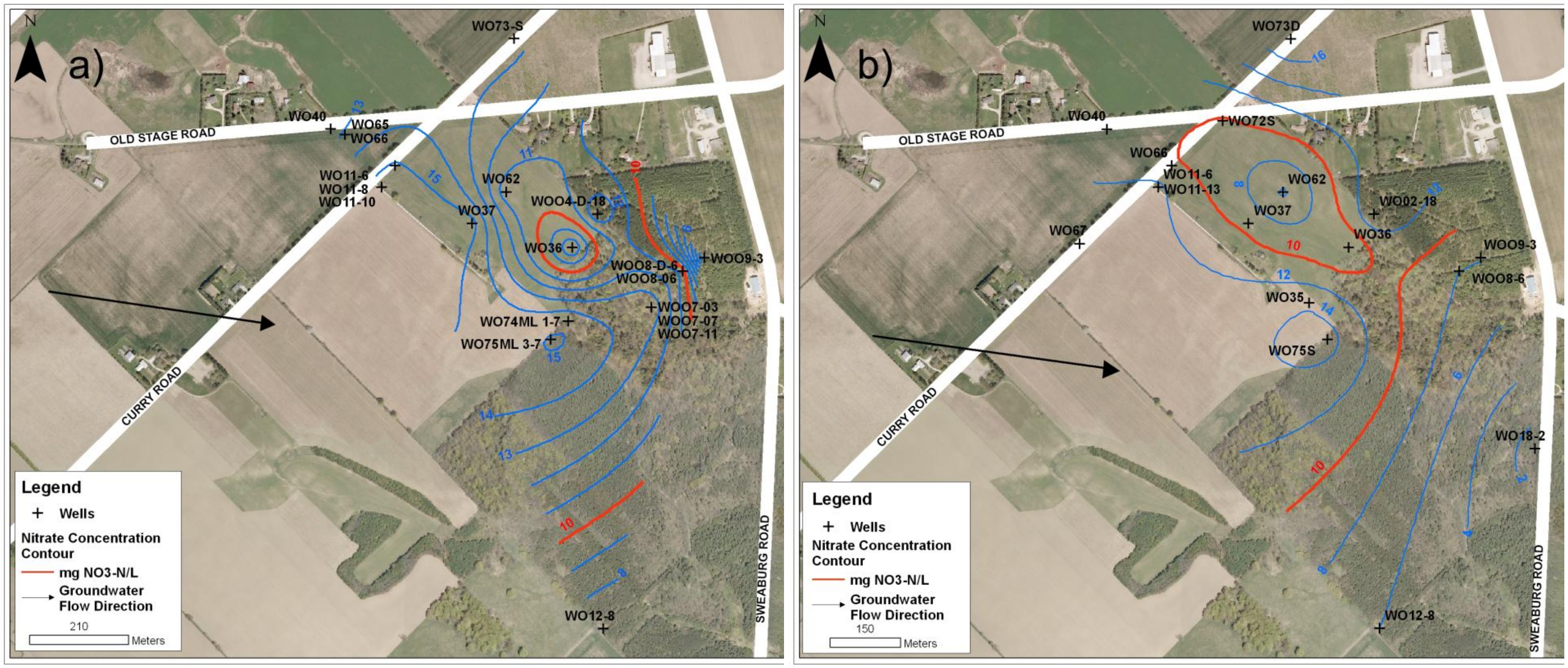


Figure 17. Nitrate concentration (mg NO_3-N/L) contours estimated from Aquifer 2 wells. Concentrations are displayed from a) October 16 to November 16, 2007 and b) May 8, 2008. Thick red lines indicate 10 mg NO_3-N/L line and arrows show general groundwater flow direction.

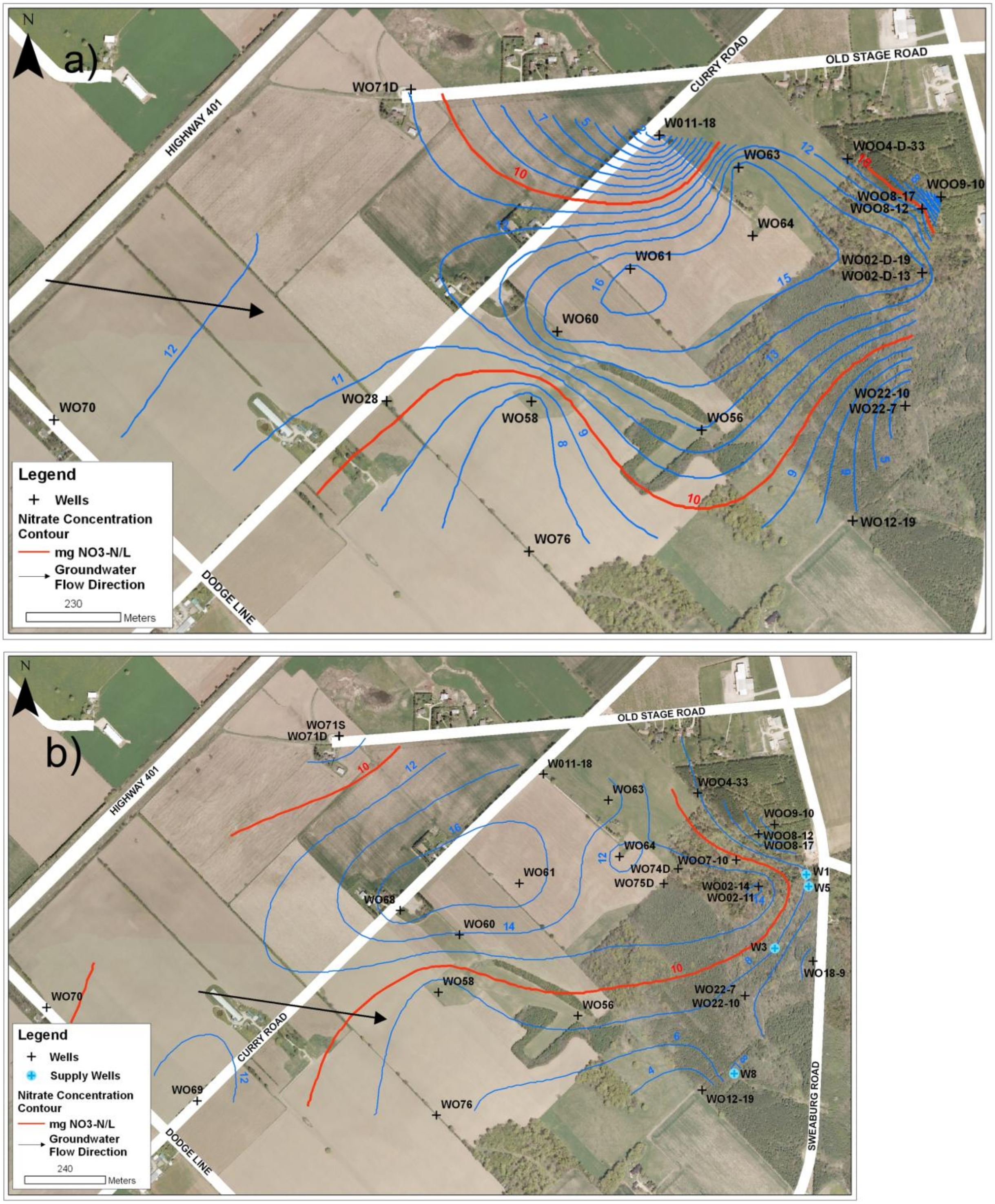


Figure 18. Nitrate concentration (mg NO_3-N/L) contours estimated from Aquifer 3 wells. Concentrations are displayed from a) October 16 to November 16, 2007 and b) May 8, 2008. Thick red lines indicate 10 mg NO_3-N/L line and arrows show general groundwater flow direction.

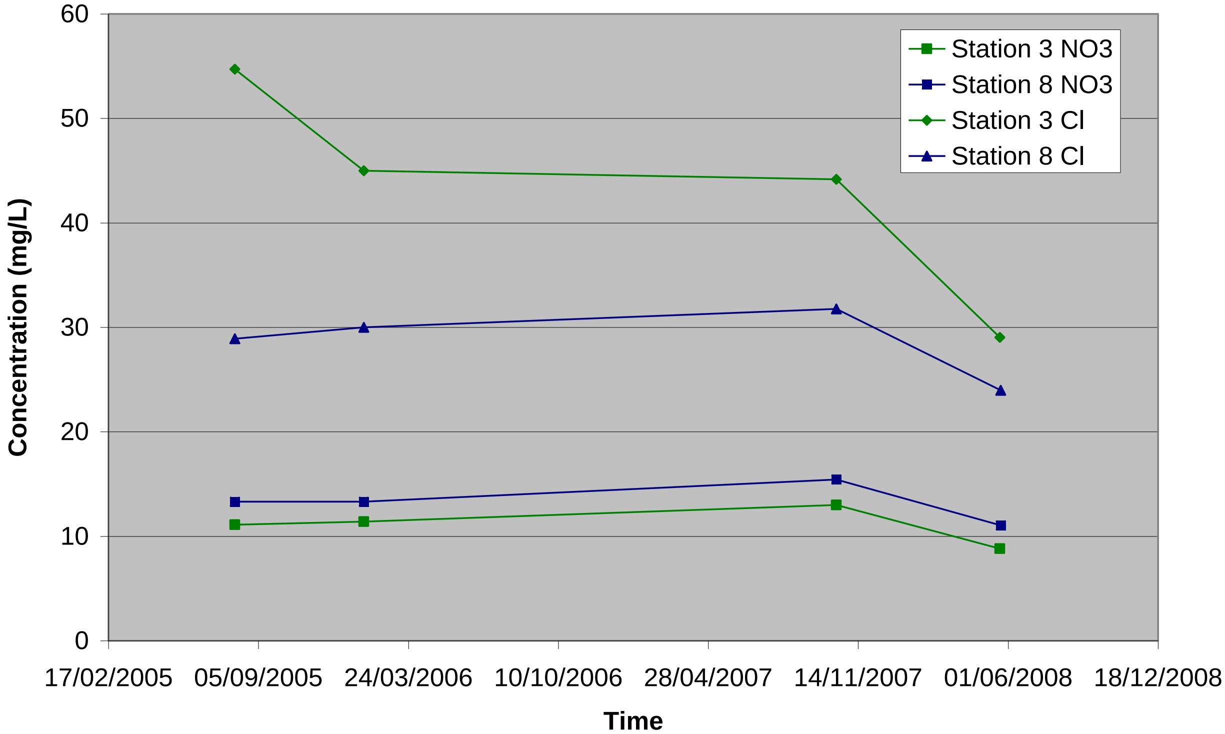


Figure 19. Nitrate and chloride concentrations at Stations 3 and 8.

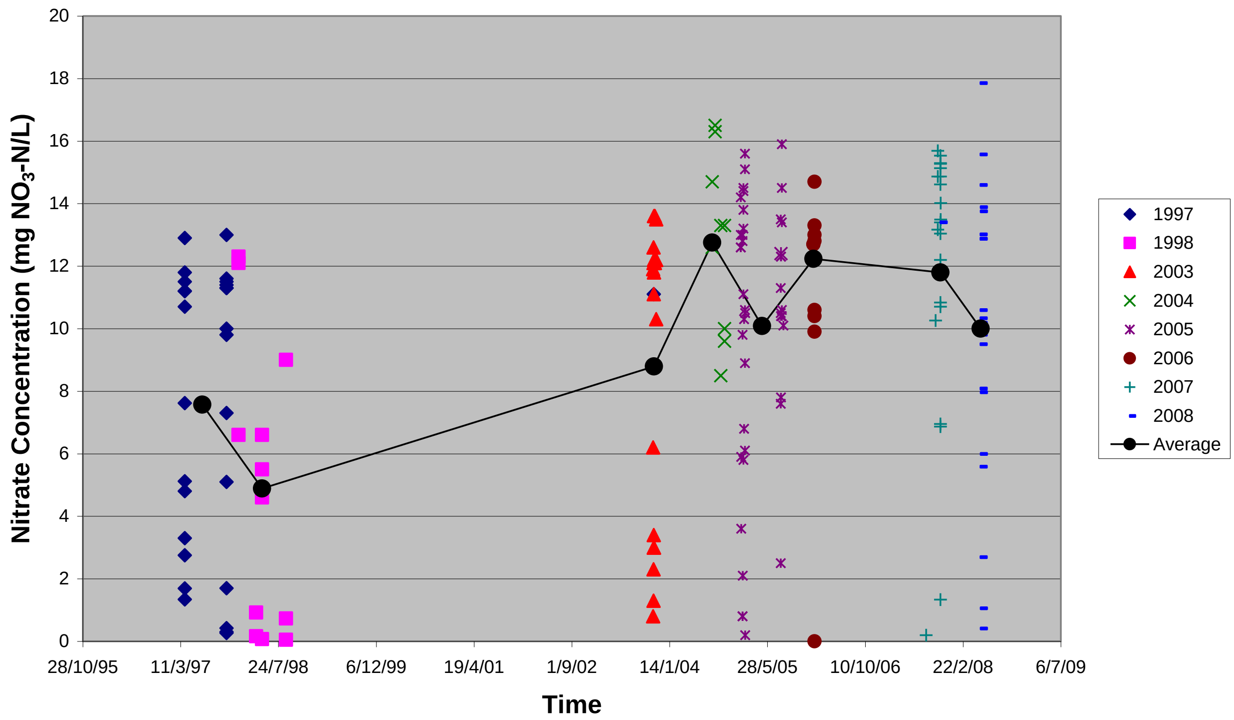


Figure 20. Nitrate concentrations within Aquifer 2 wells.

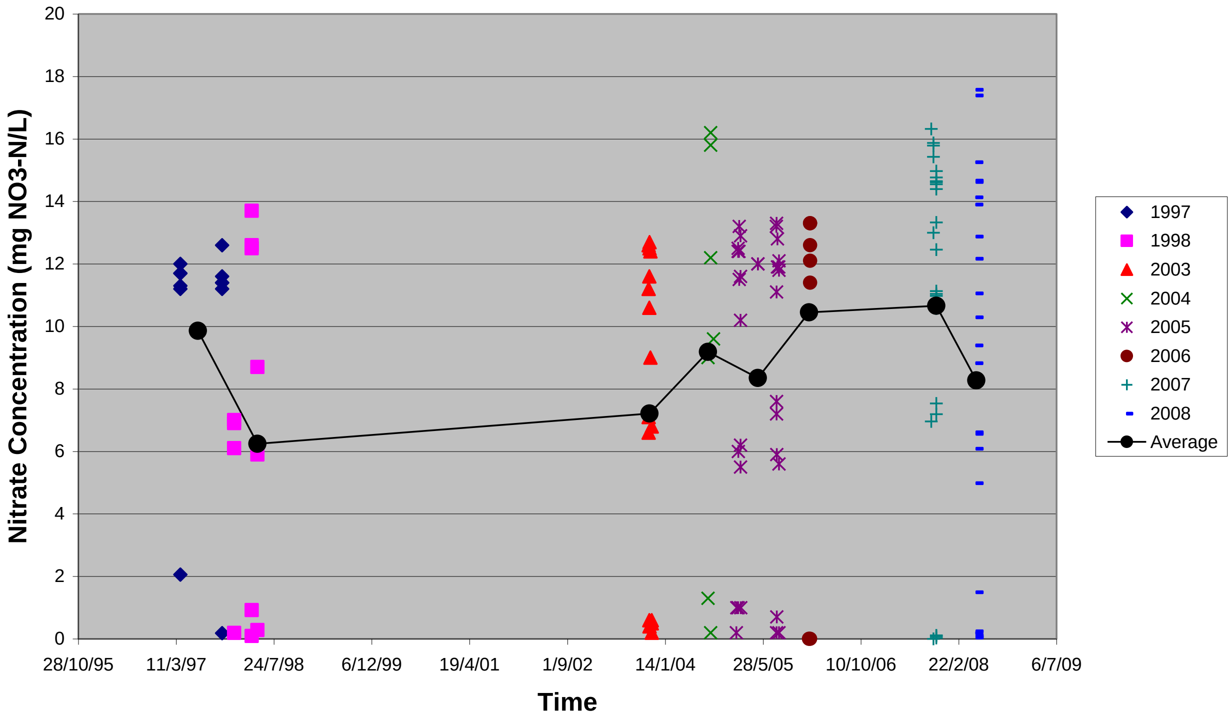


Figure 21. Nitrate concentrations within Aquifer 3 wells.

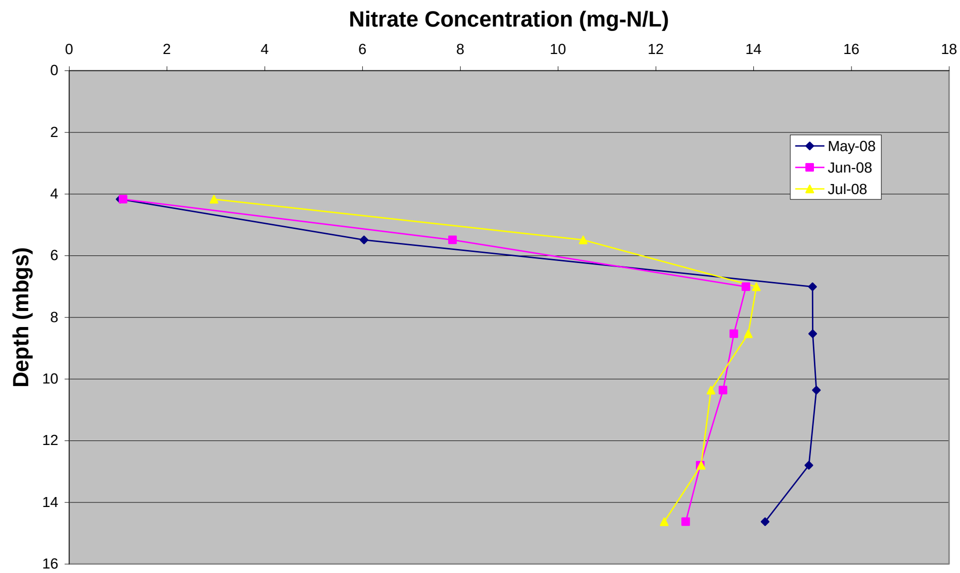


Figure 22. Nitrate concentrations at CMT well WO74-ML.

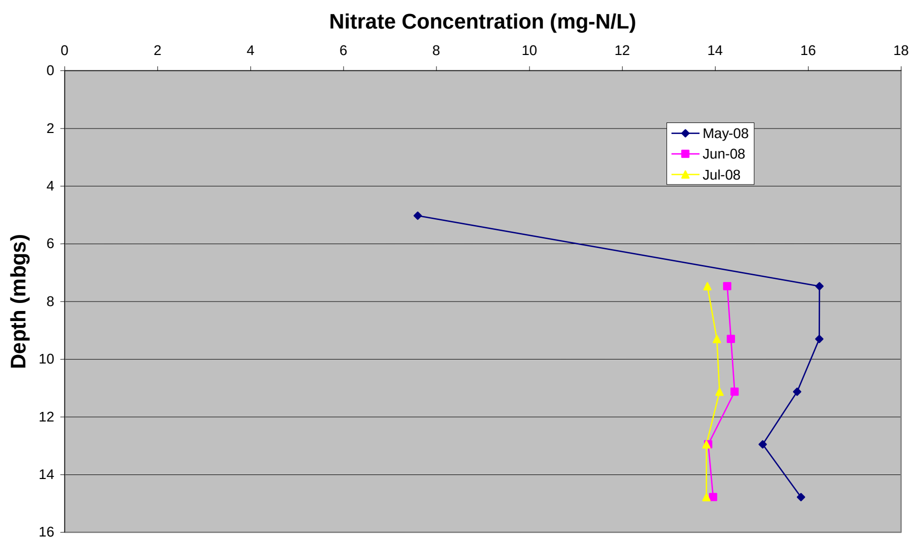


Figure 23. Nitrate concentrations at CMT well WO75-ML.

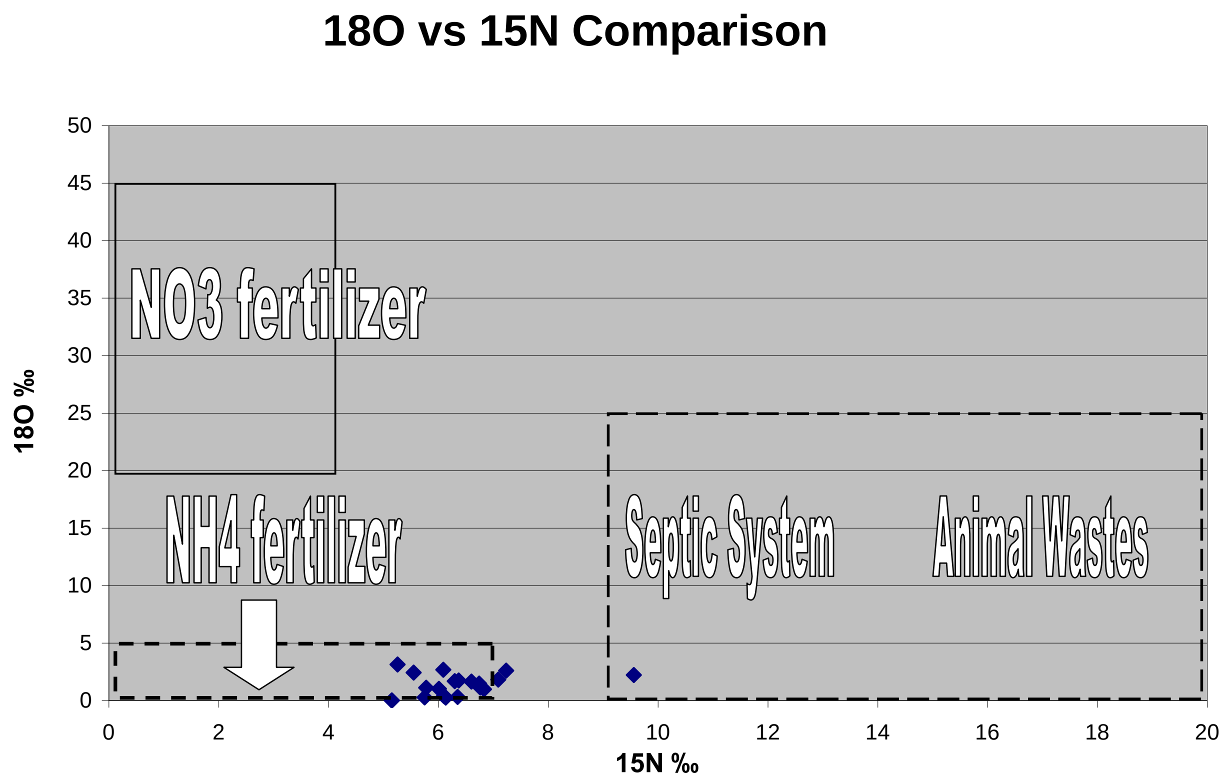


Figure 24. Nitrate isotope comparison.

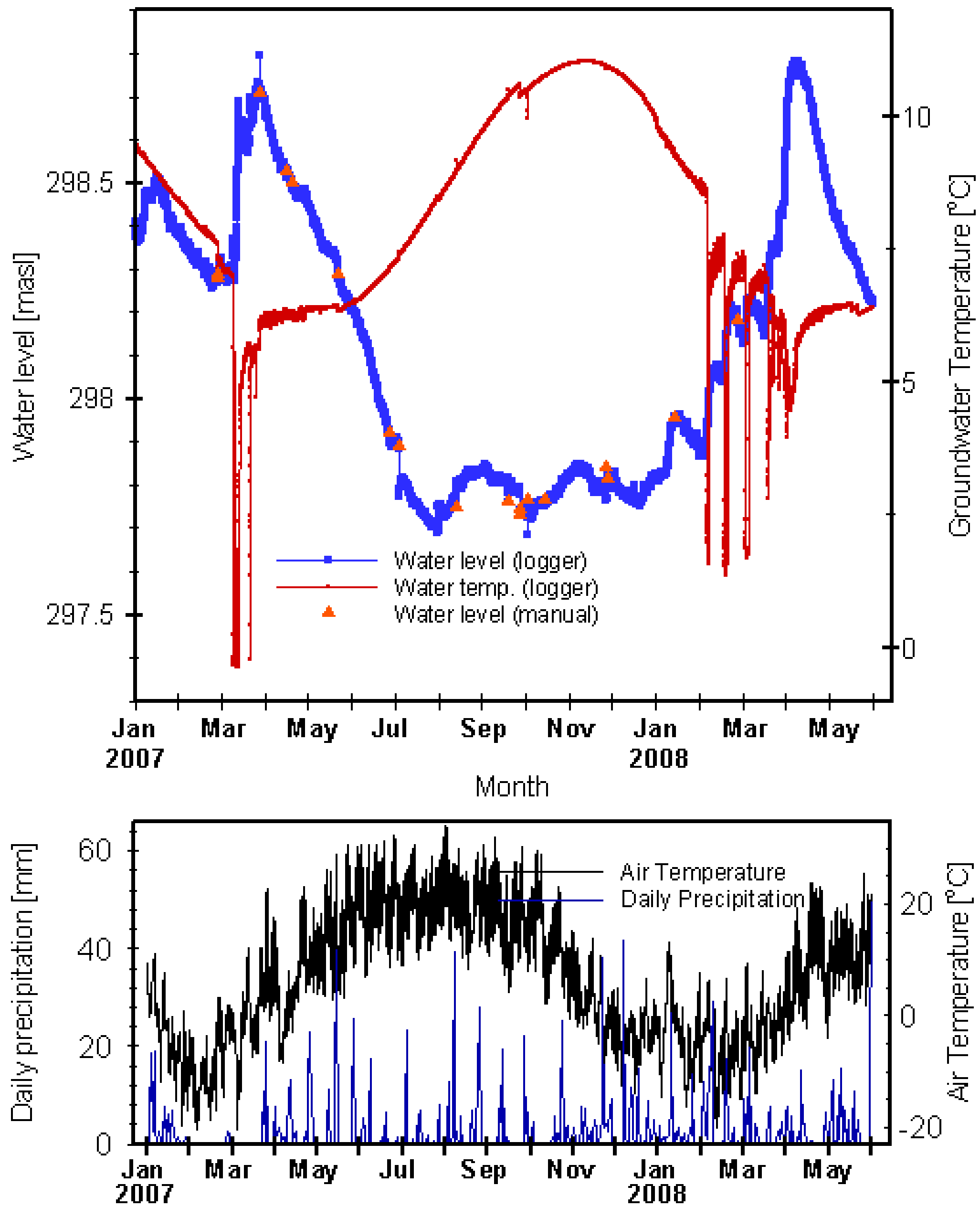


Figure 25. Temperature, water level and precipitation at Station 1 (January 1, 2007 – May 31, 2008).

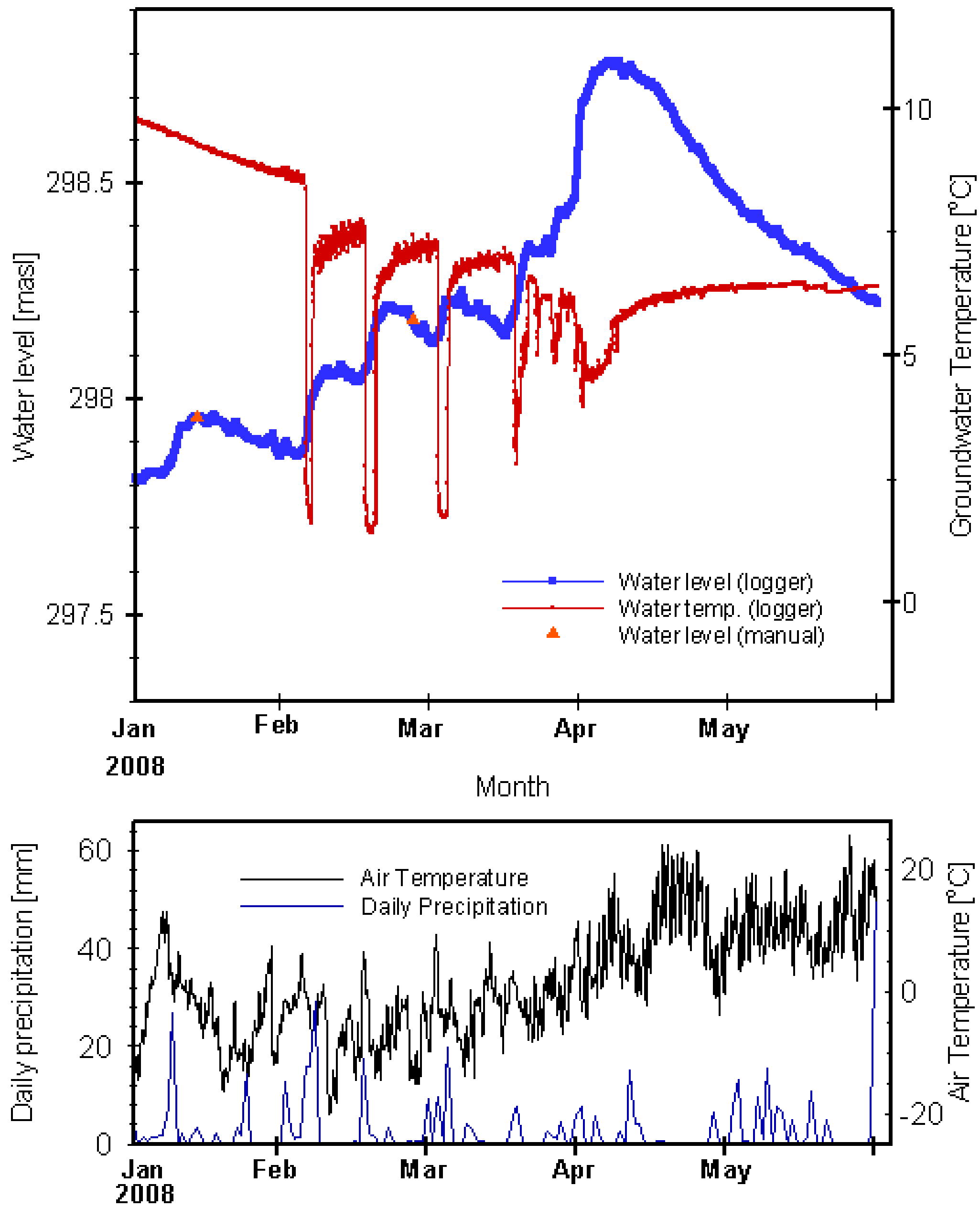


Figure 26. Temperature, water level and precipitation at Station 1 (January 1 - May 31, 2008).

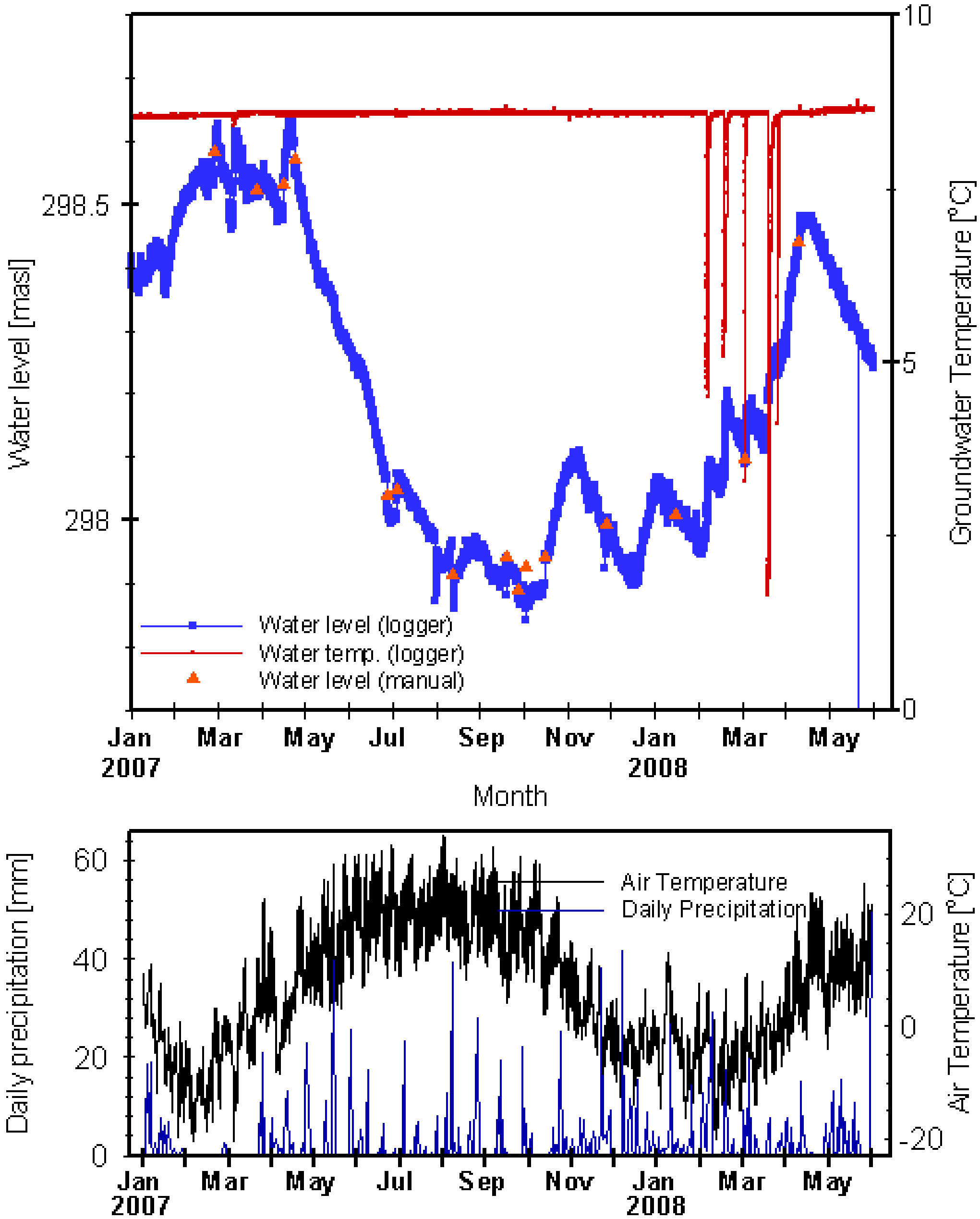


Figure 27. Temperature, water level and precipitation at Station 3 (January 1, 2007 - May 31, 2008).

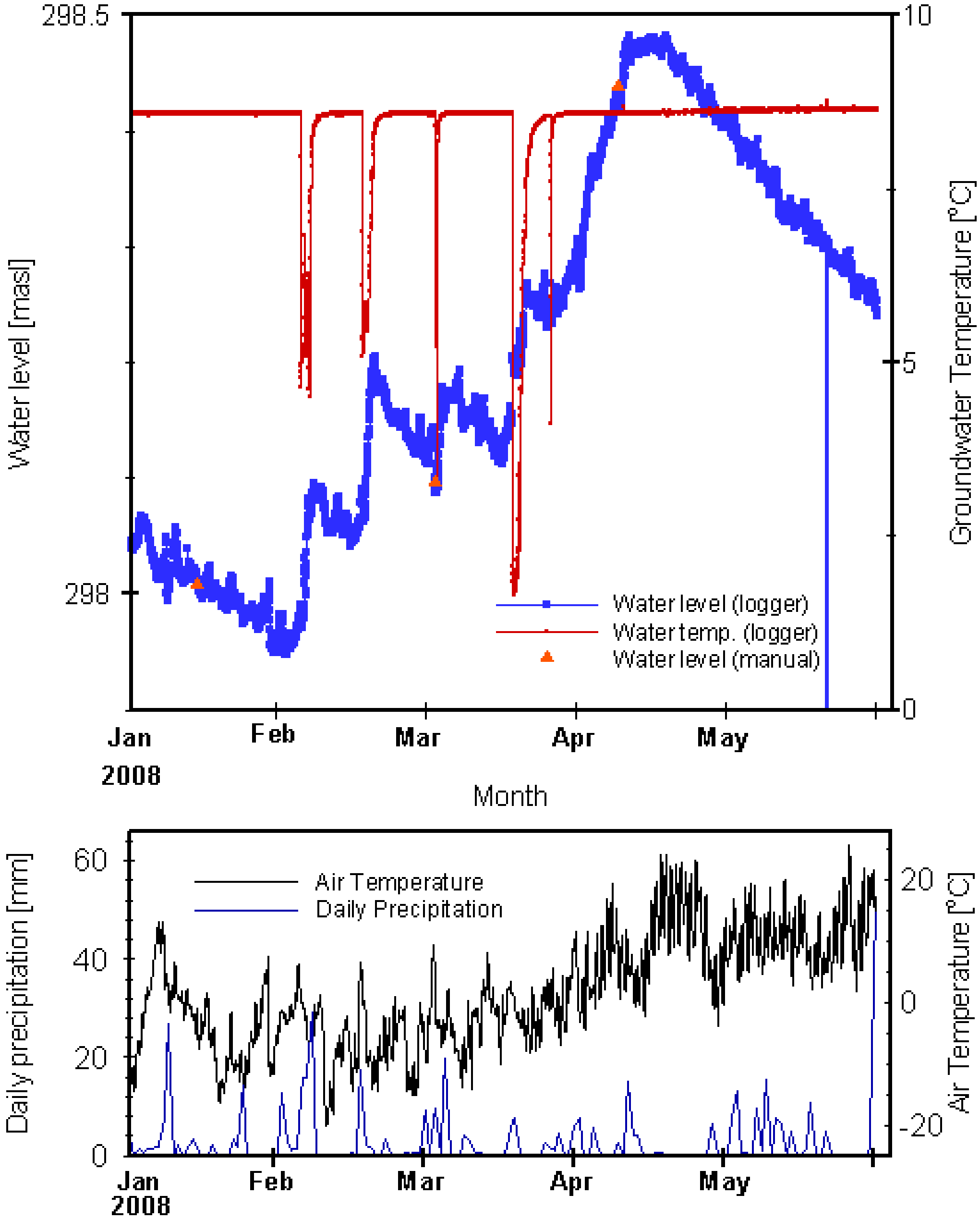


Figure 28. Temperature, water level and precipitation at Station 3 (January 1 - May 31, 2008).

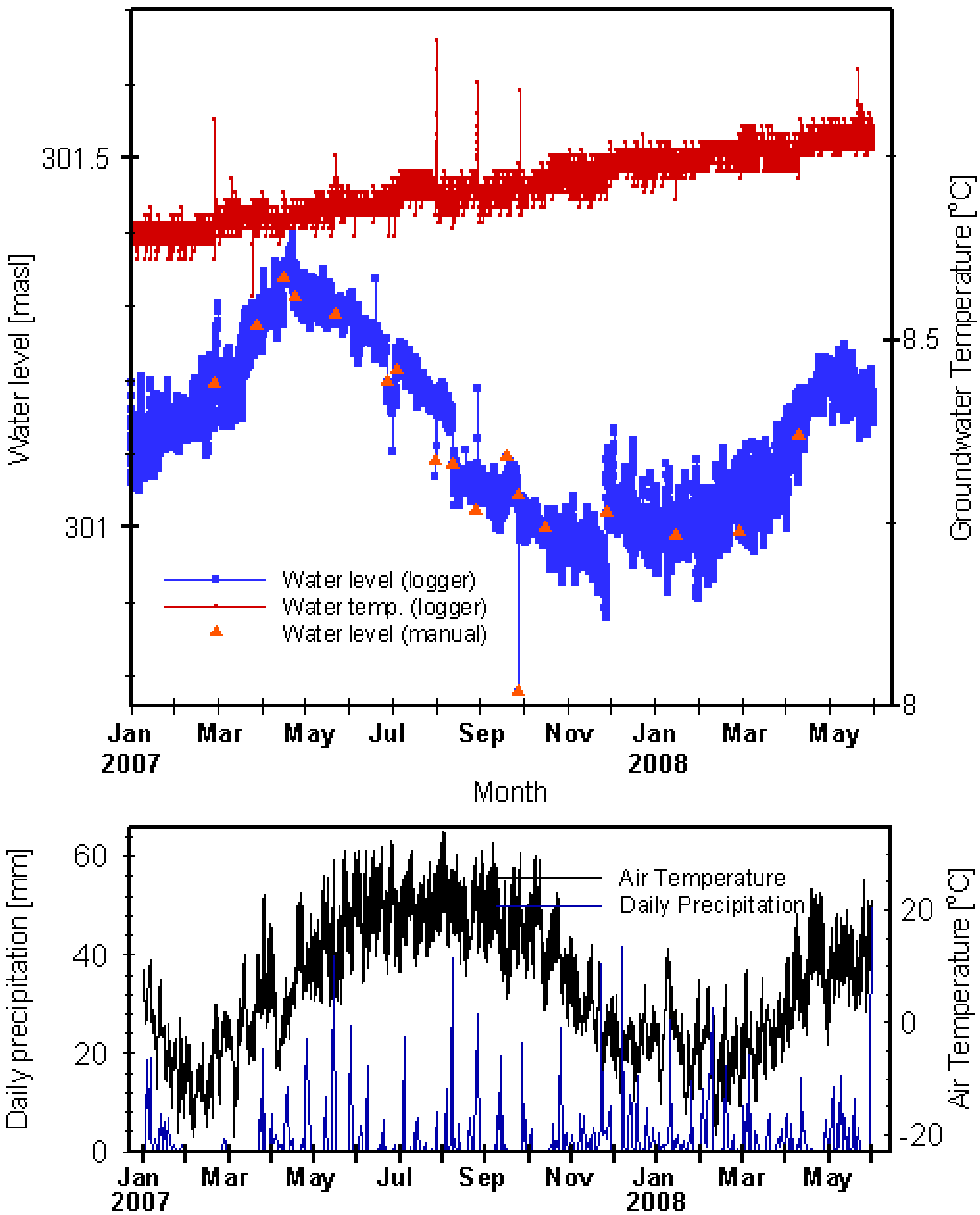


Figure 29. Temperature, water level and precipitation at Station 2 (January 1, 2007 - May 31, 2008).

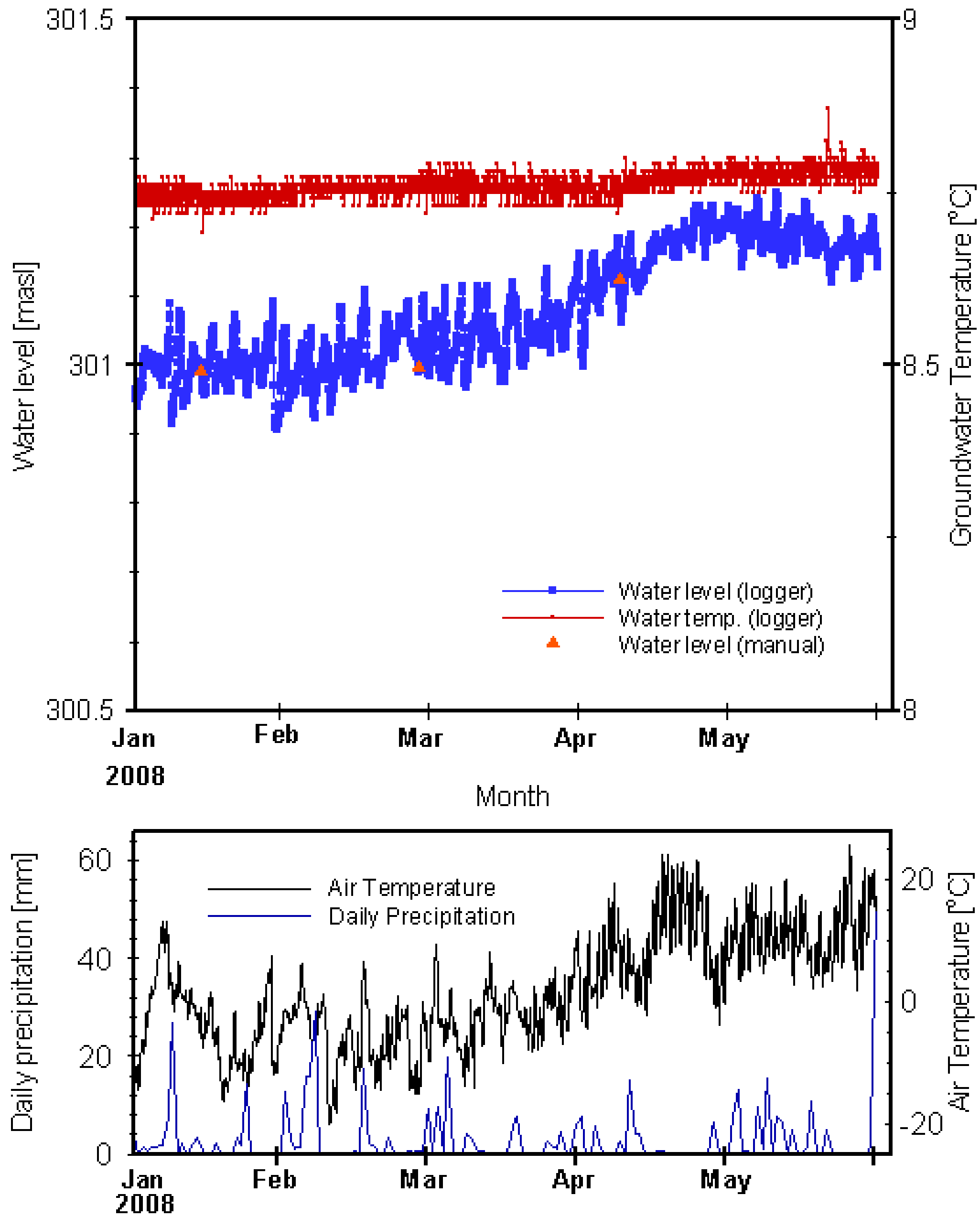


Figure 30. Temperature, water level and precipitation at Station 2 (January 1 - May 31, 2008).

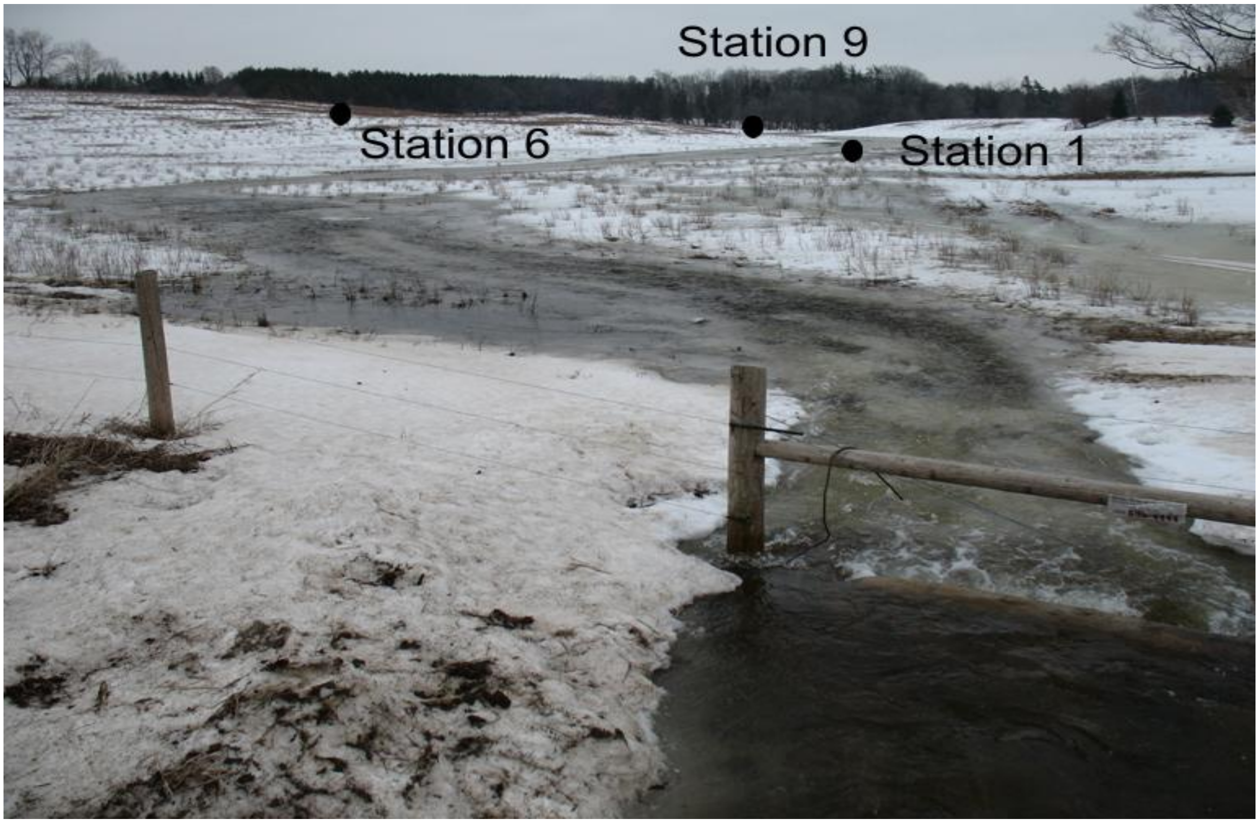


Figure 31. Melt water stream flowing southward across station 1 along glacial outwash channel, March 18, 2008 (photo by Mike Christie).

Figure 32. Melt water stream flowing from station 5 (off frame to the right) across station 3, February 5, 2008 (photo by author).

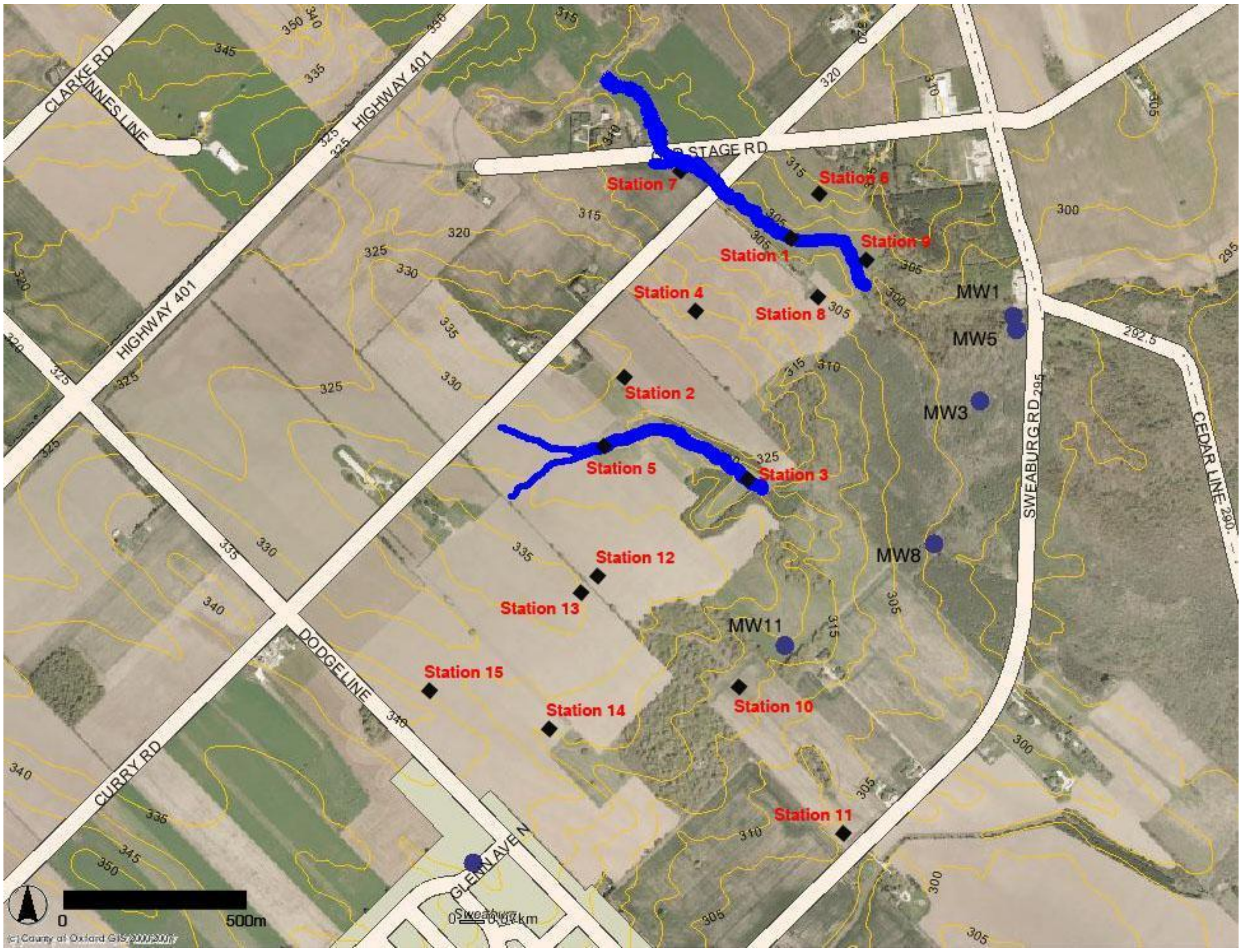


Figure 33. Location of ephemeral melt water streams (shown in blue).

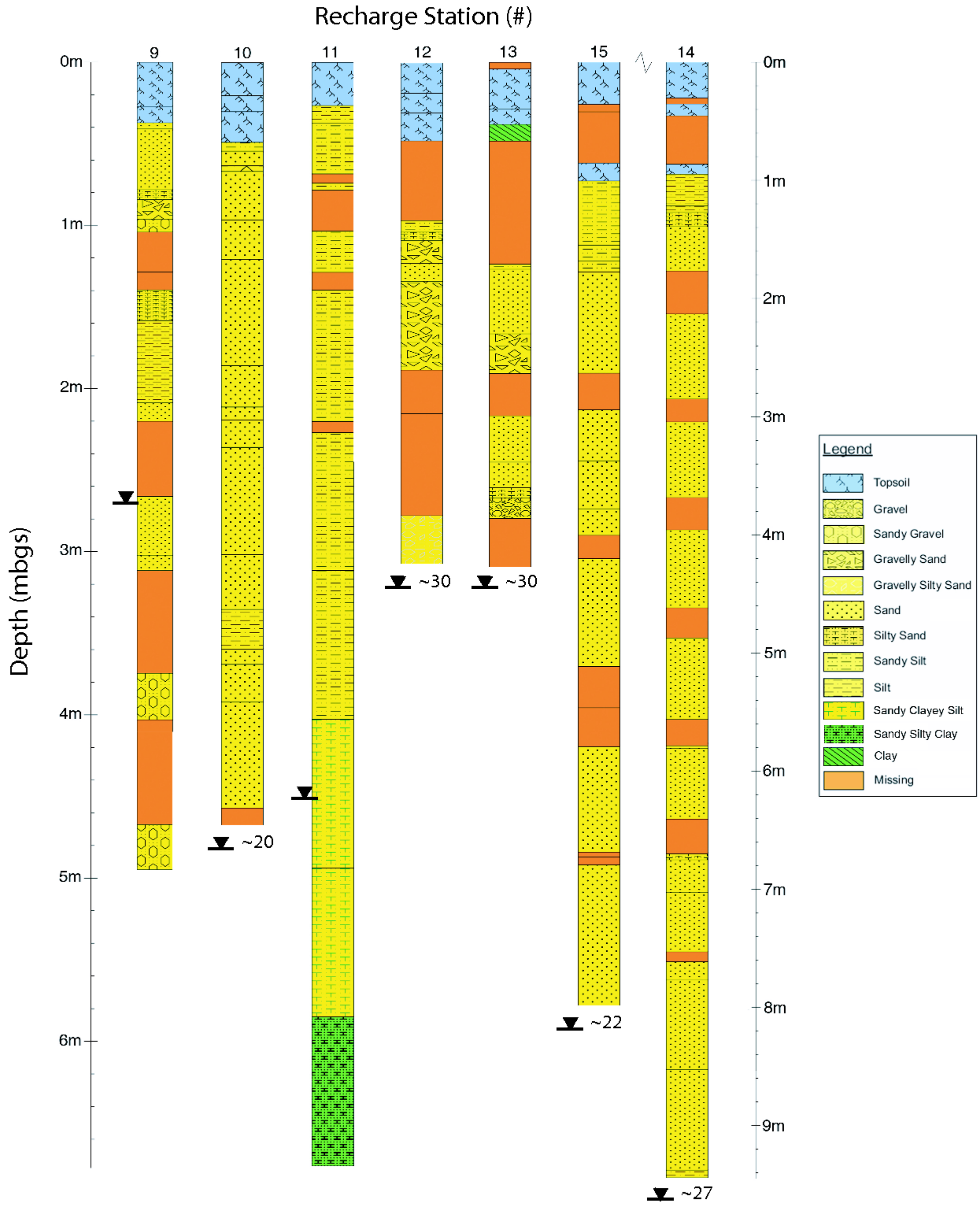


Figure 34. Geology and water table locations at stations 9-15.

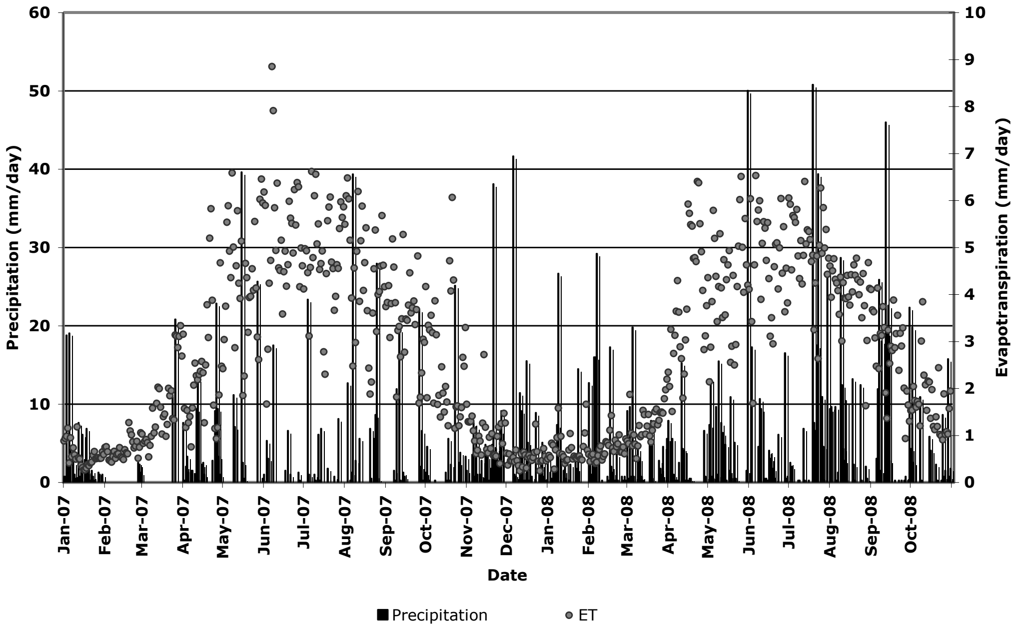


Figure 35. Precipitation and evapotranspiration at grass-cropped Stations 1, 3, 5, 6, 8 and 9.

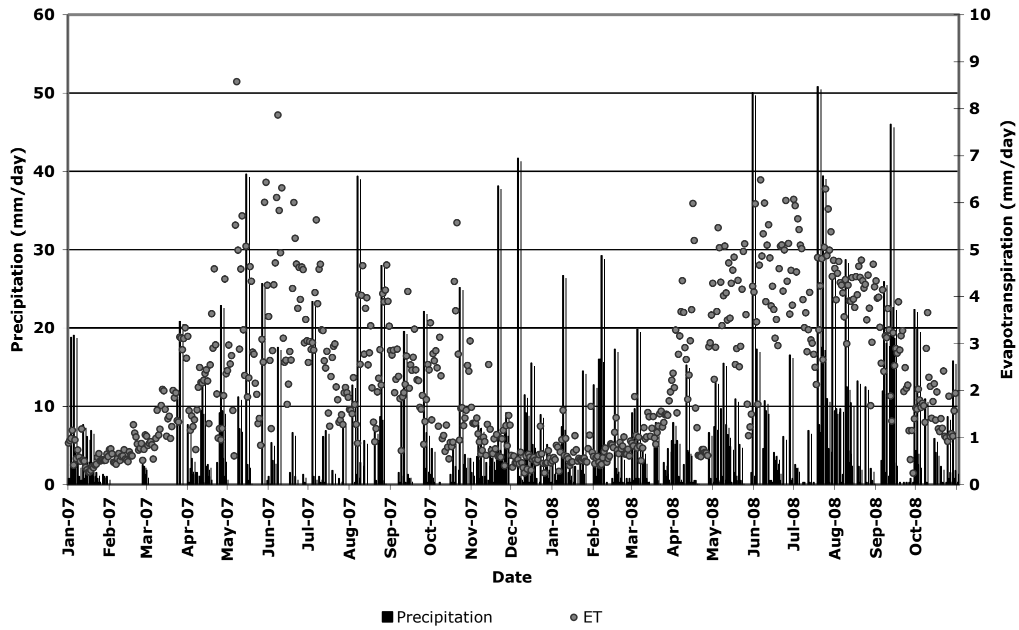


Figure 36. Precipitation and evapotranspiration at corn/soy/winter wheat-cropped Stations 10, 11, 14 and 15.

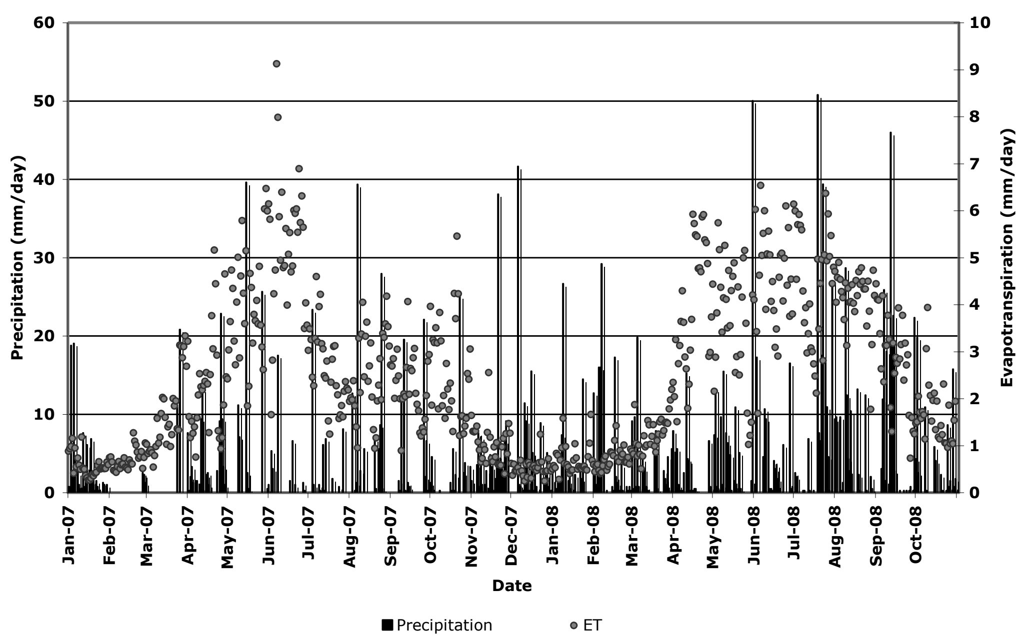


Figure 37. Precipitation and evapotranspiration at winter wheat/corn-cropped Stations 2 and 4.

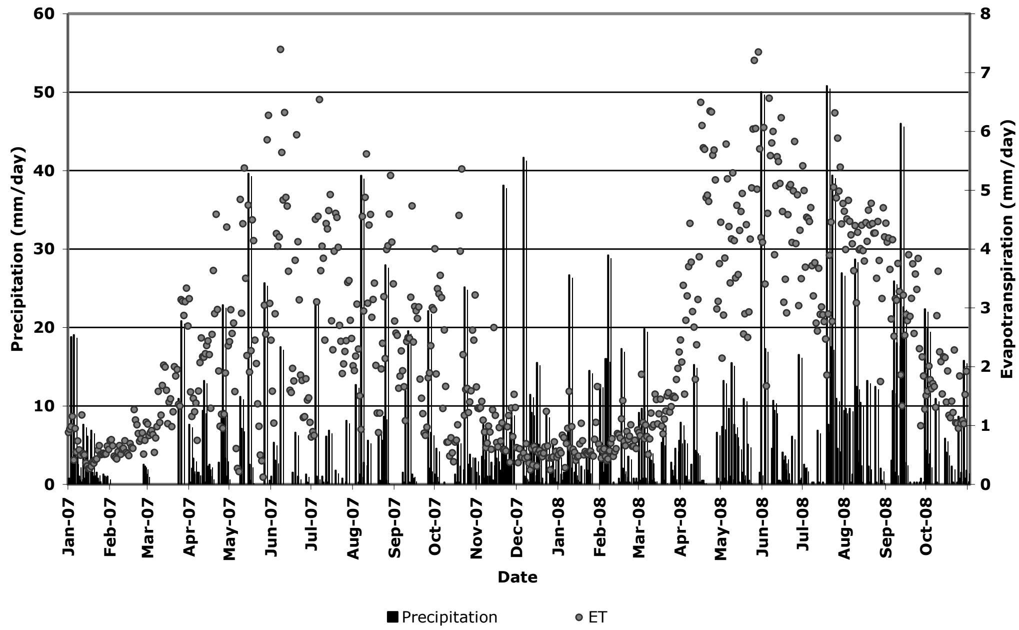


Figure 38. Precipitation and evapotranspiration at Roman beans/winter wheat-cropped Station 12.

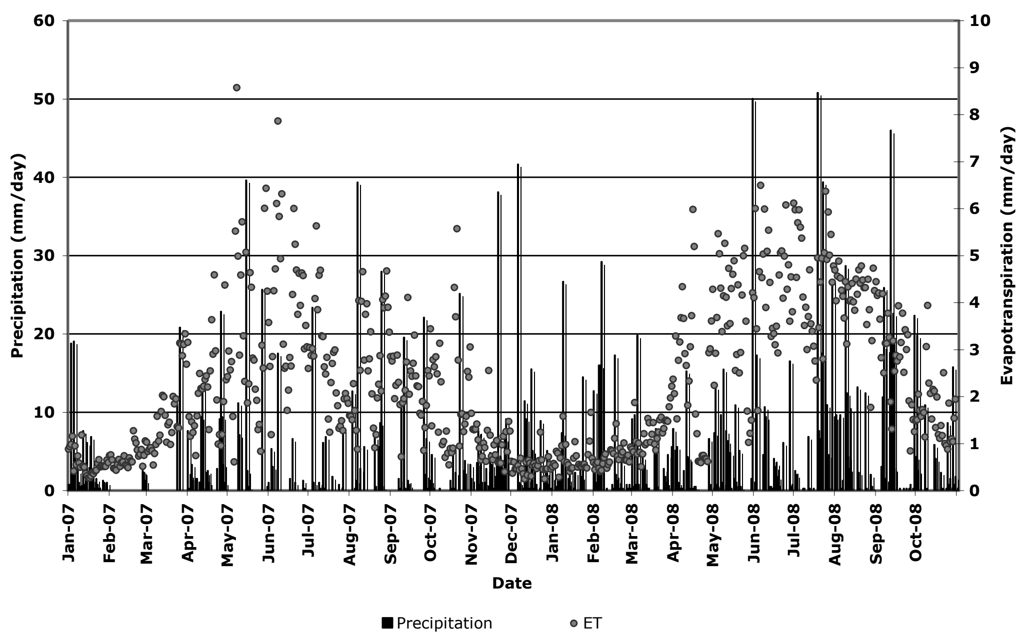


Figure 39. Precipitation and evapotranspiration at corn-cropped Station 13.

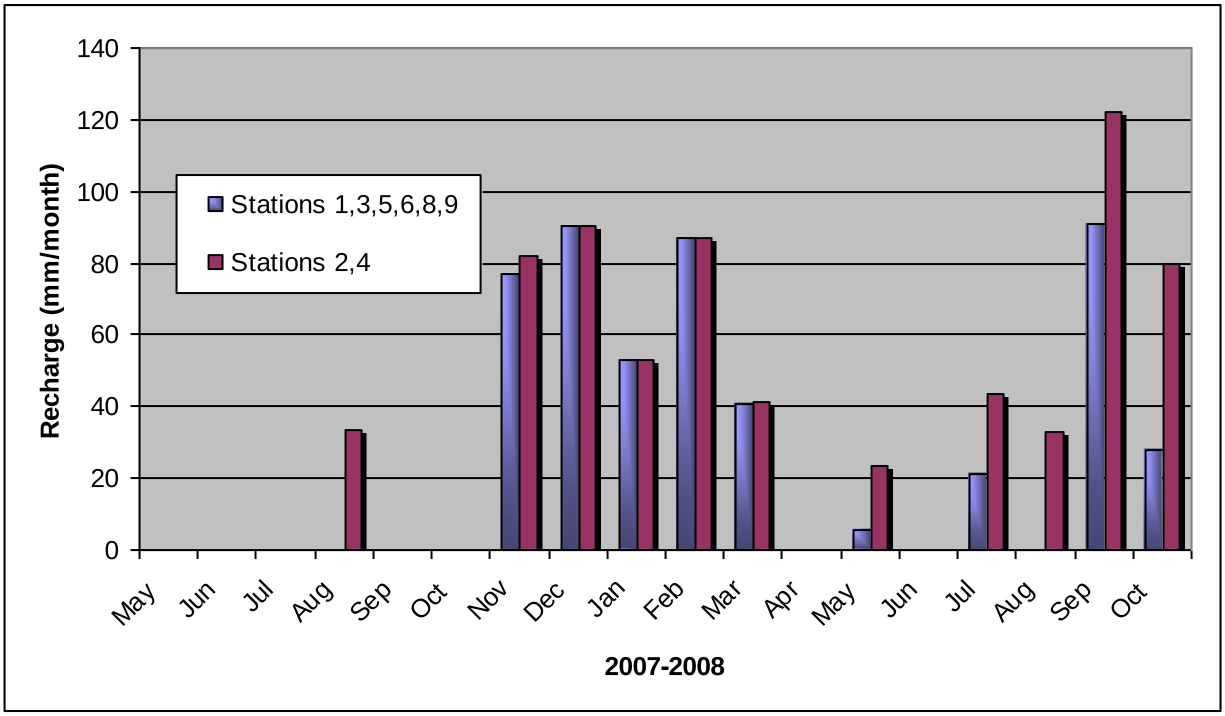


Figure 40. Water balance recharge estimates for May 2007 - October 2008.

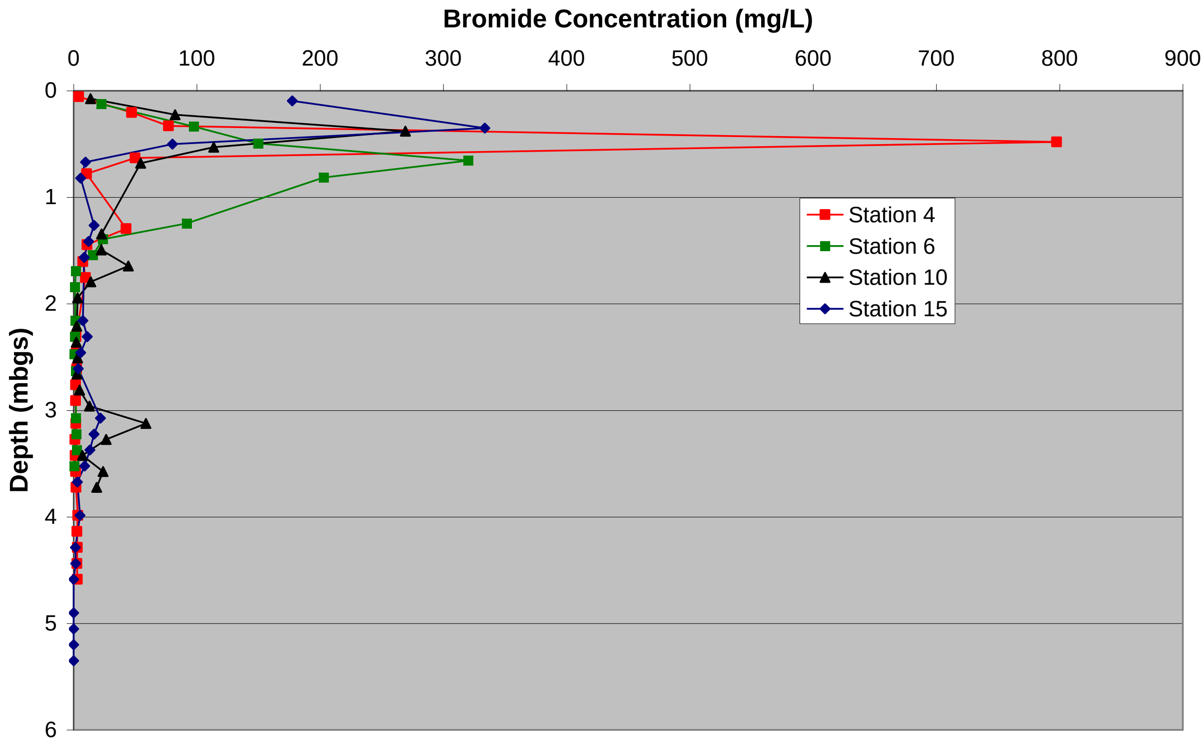


Figure 41. Bromide concentrations at stations 4, 6, 10 and 15.

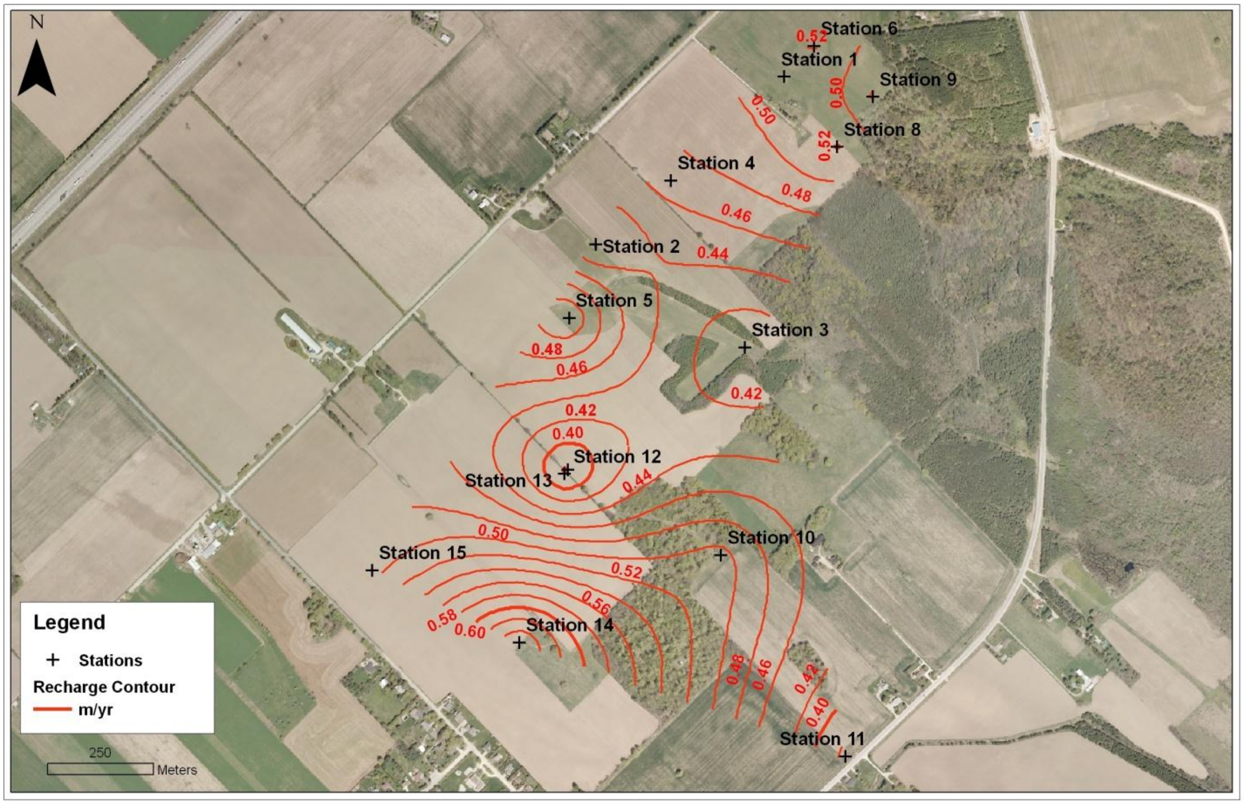


Figure 42. Contoured recharge estimates at each station from May 2007 to May 2008.

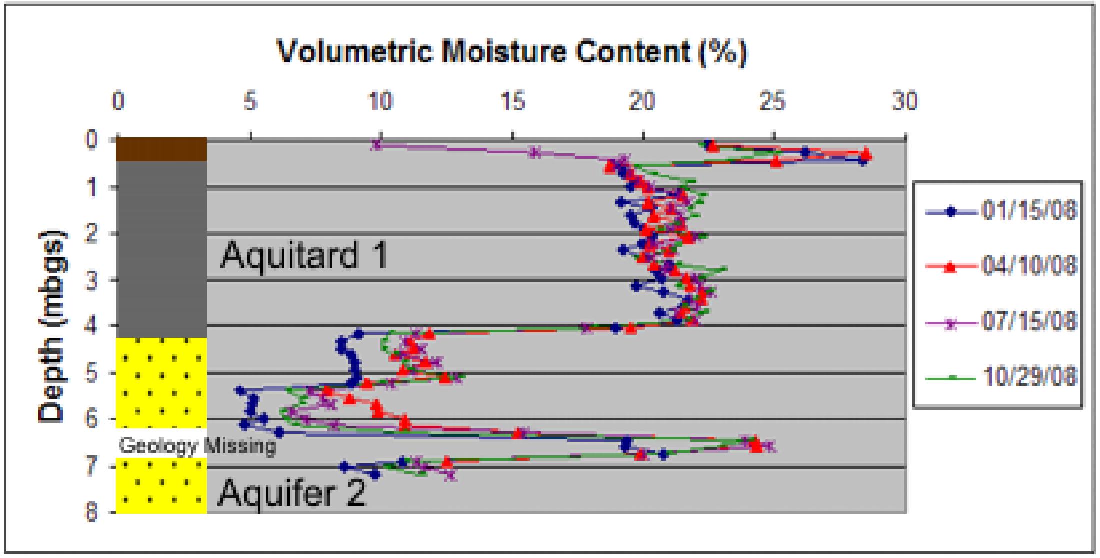


Figure 43. Station 2 (AT11) neutron probe measured soil moisture profile.

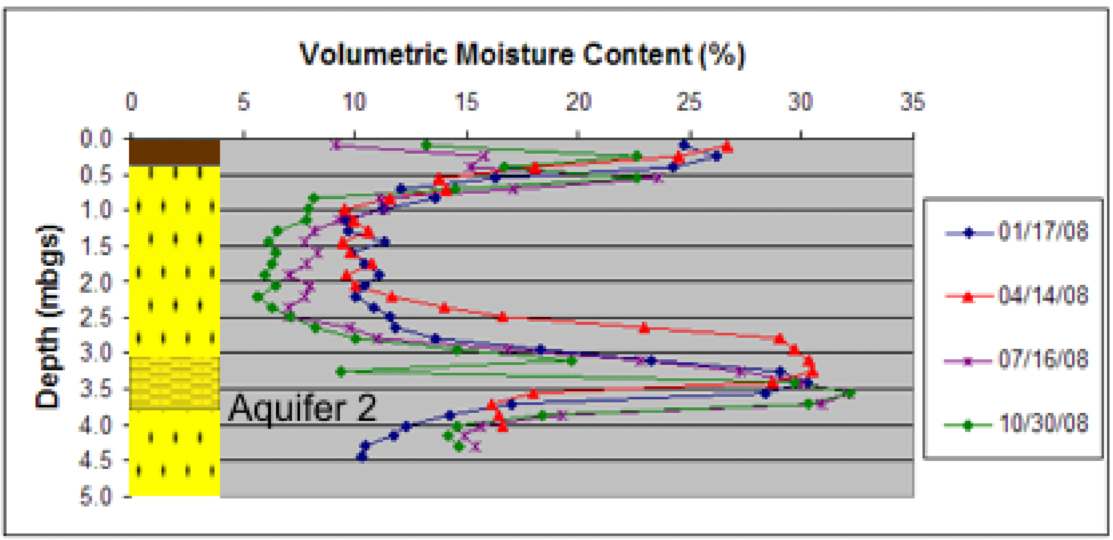


Figure 44. Station 10 (AT21) neutron probe measured soil moisture profile.

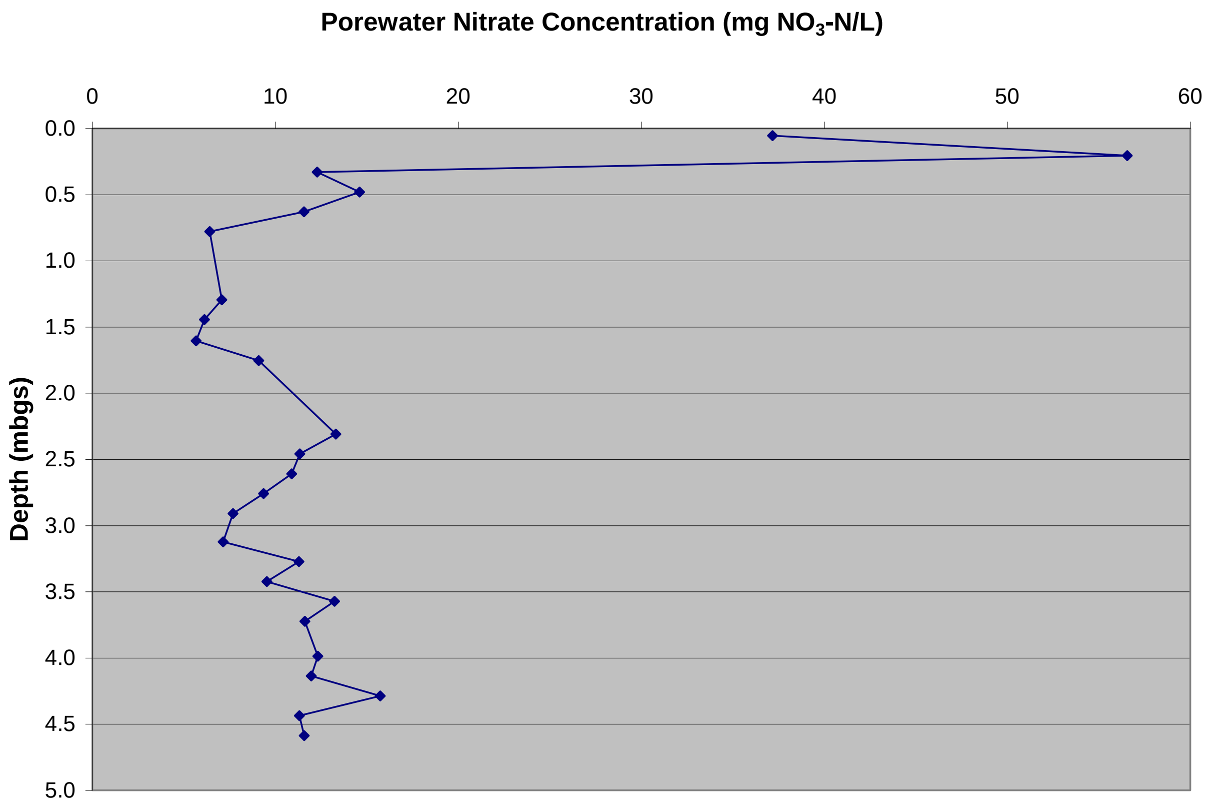


Figure 45. Porewater nitrate concentration versus depth at Station 4 (May 2008).

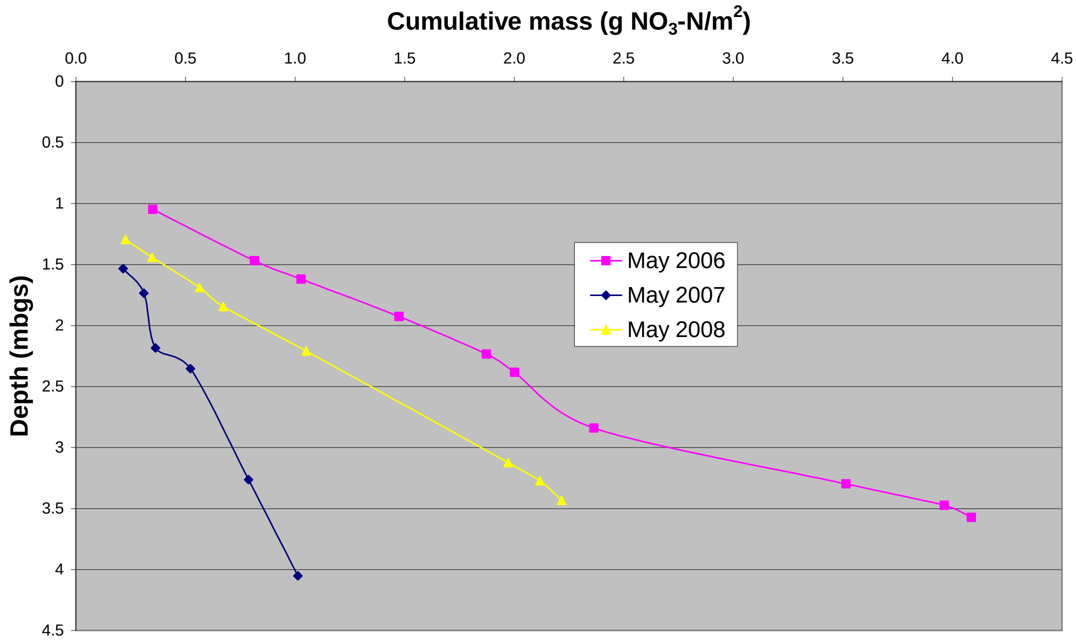


Figure 46. Cumulative nitrate mass versus depth at Station 1.

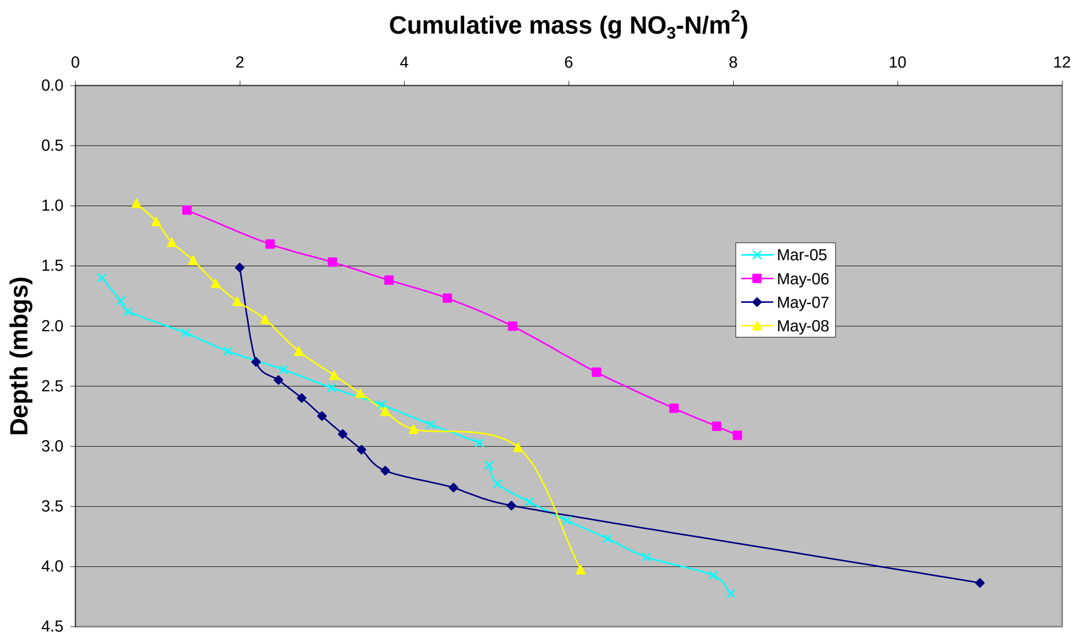


Figure 47. Cumulative nitrate mass versus depth at Station 2.

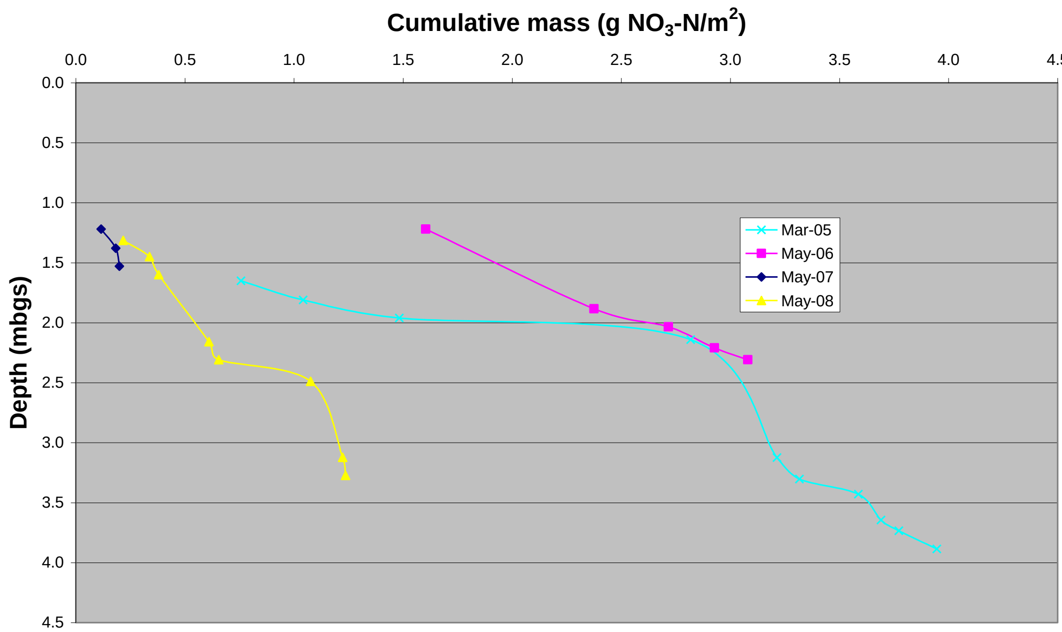


Figure 48. Cumulative nitrate mass versus depth at Station 3.

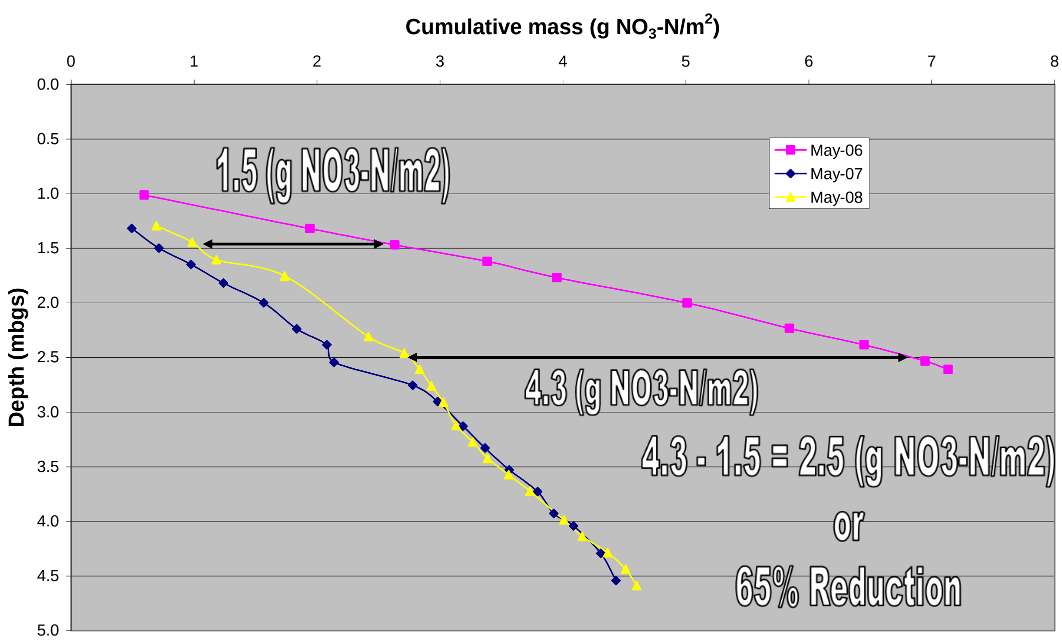


Figure 49. Cumulative nitrate mass versus depth at Station 4.

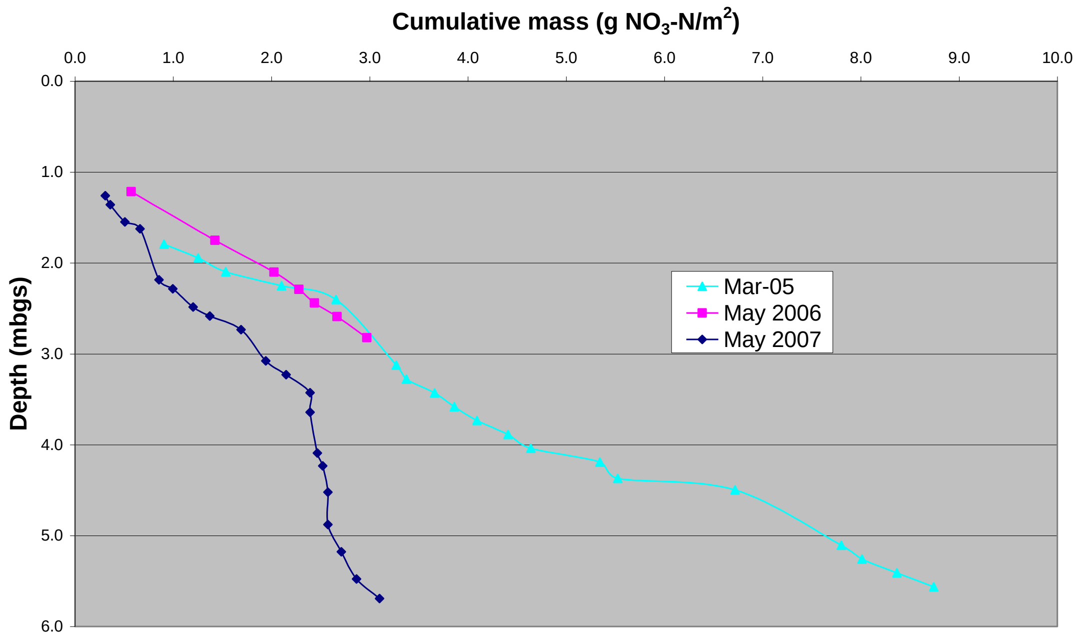


Figure 50. Cumulative nitrate mass versus depth at Station 5.

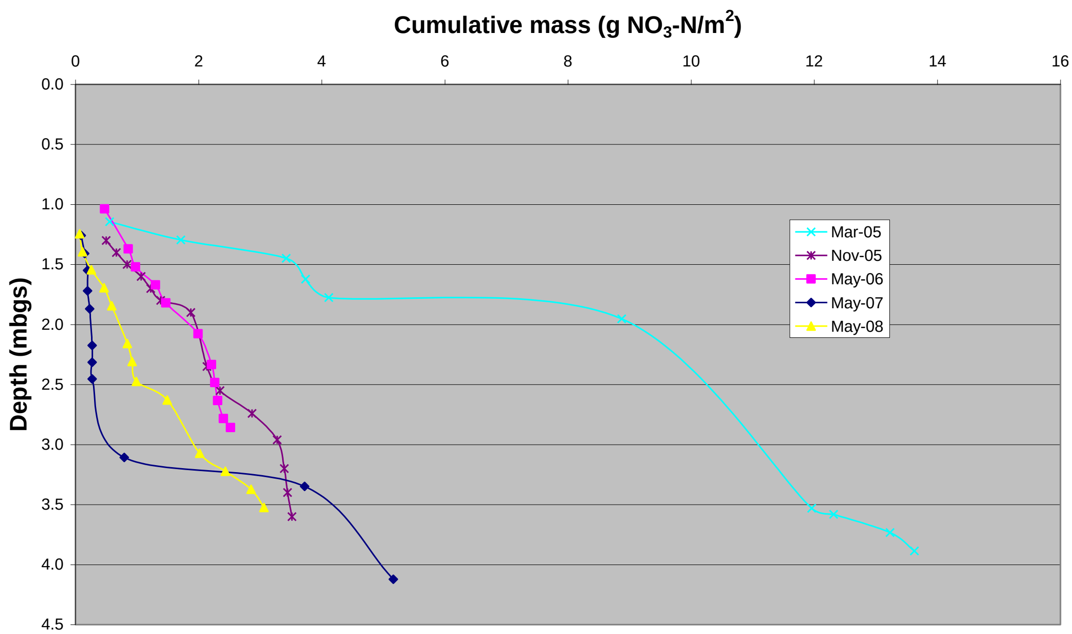


Figure 51. Cumulative nitrate mass versus depth at Station 6.

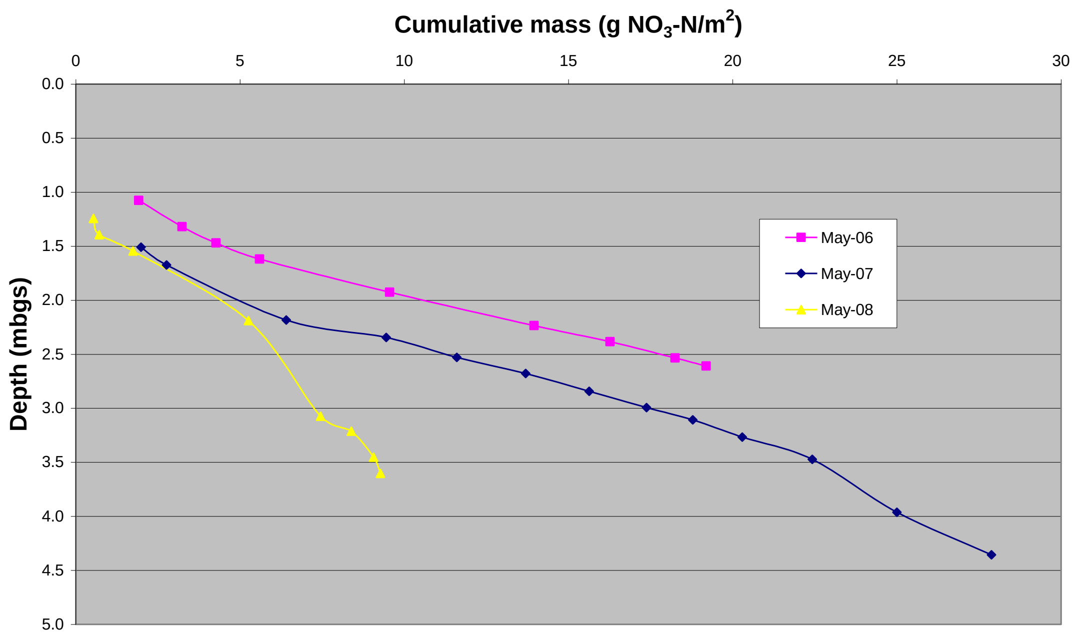


Figure 52. Cumulative nitrate mass versus depth at Station 8.

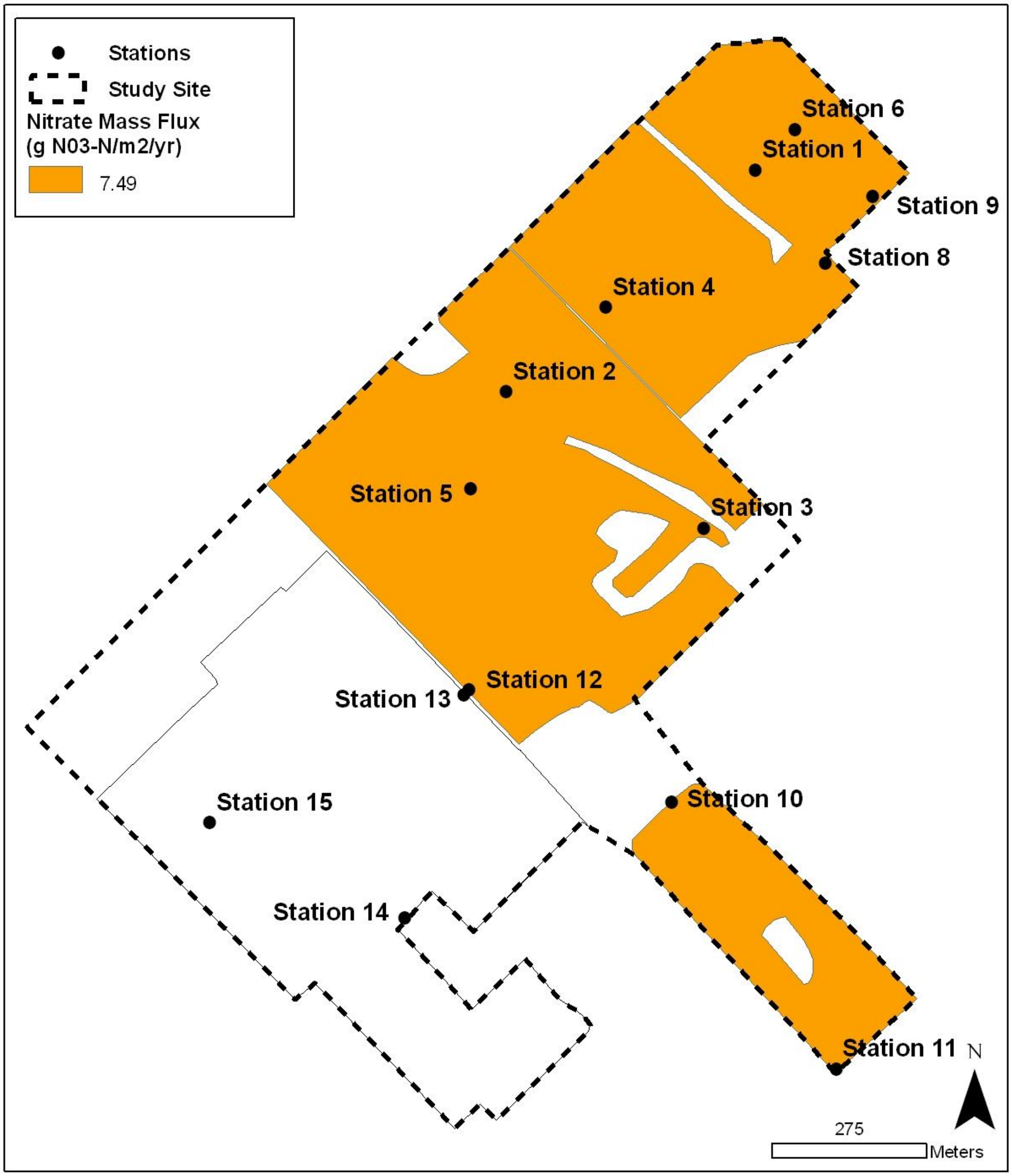


Figure 53. Upscaled nitrate mass flux (May 2006) used to determine nitrate loading within Parcel B (shaded) using method 1: average porewater nitrate concentrations.

Figure 54. Extropolated nitrate mass flux (May 2008) used to determine nitrate loading using method 1: average porewater nitrate concentrations.

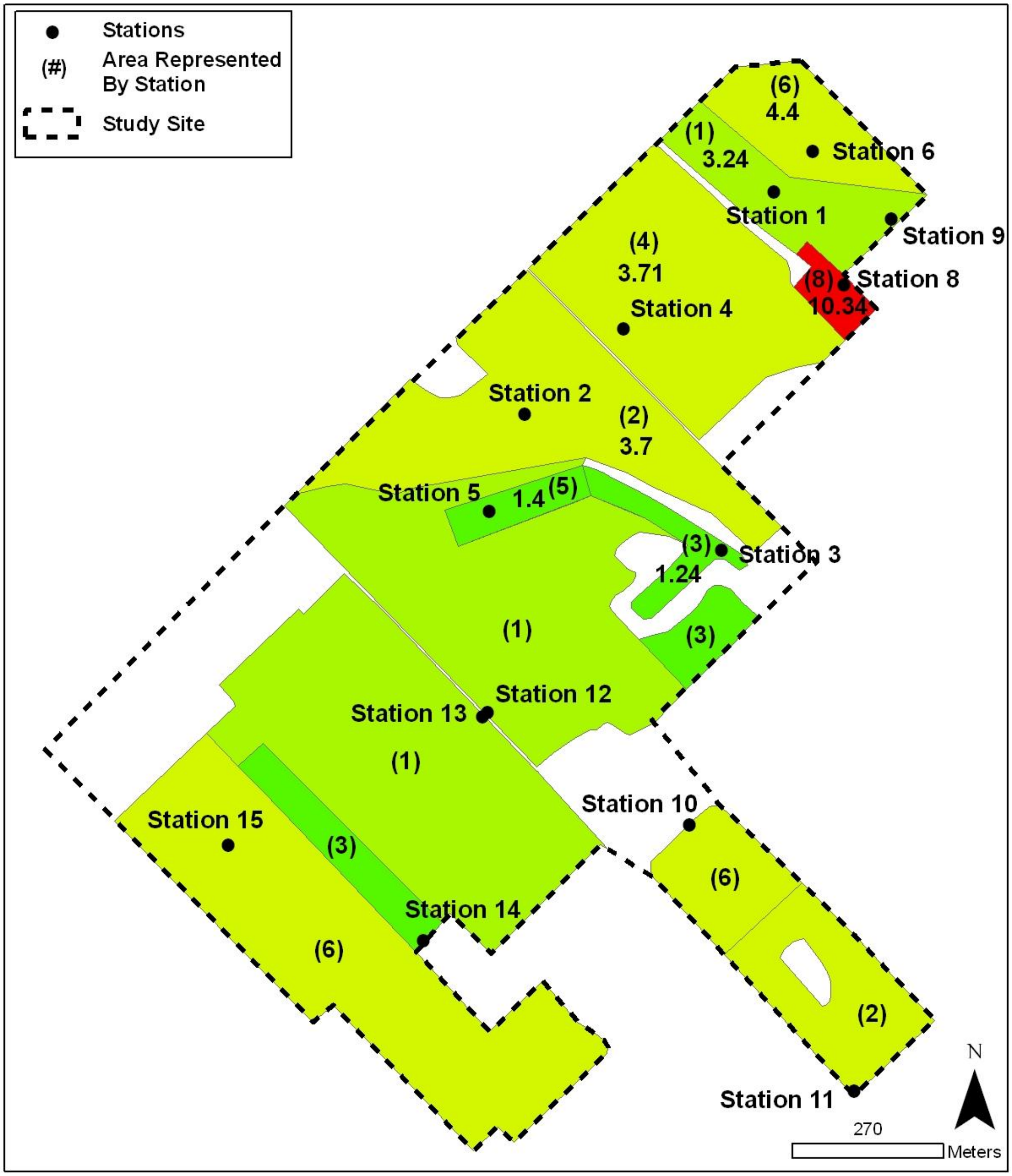


Figure 55. Upscaled mass flux used to determine nitrate loading using method 2: geology, topography, recharge, field observations criteria.

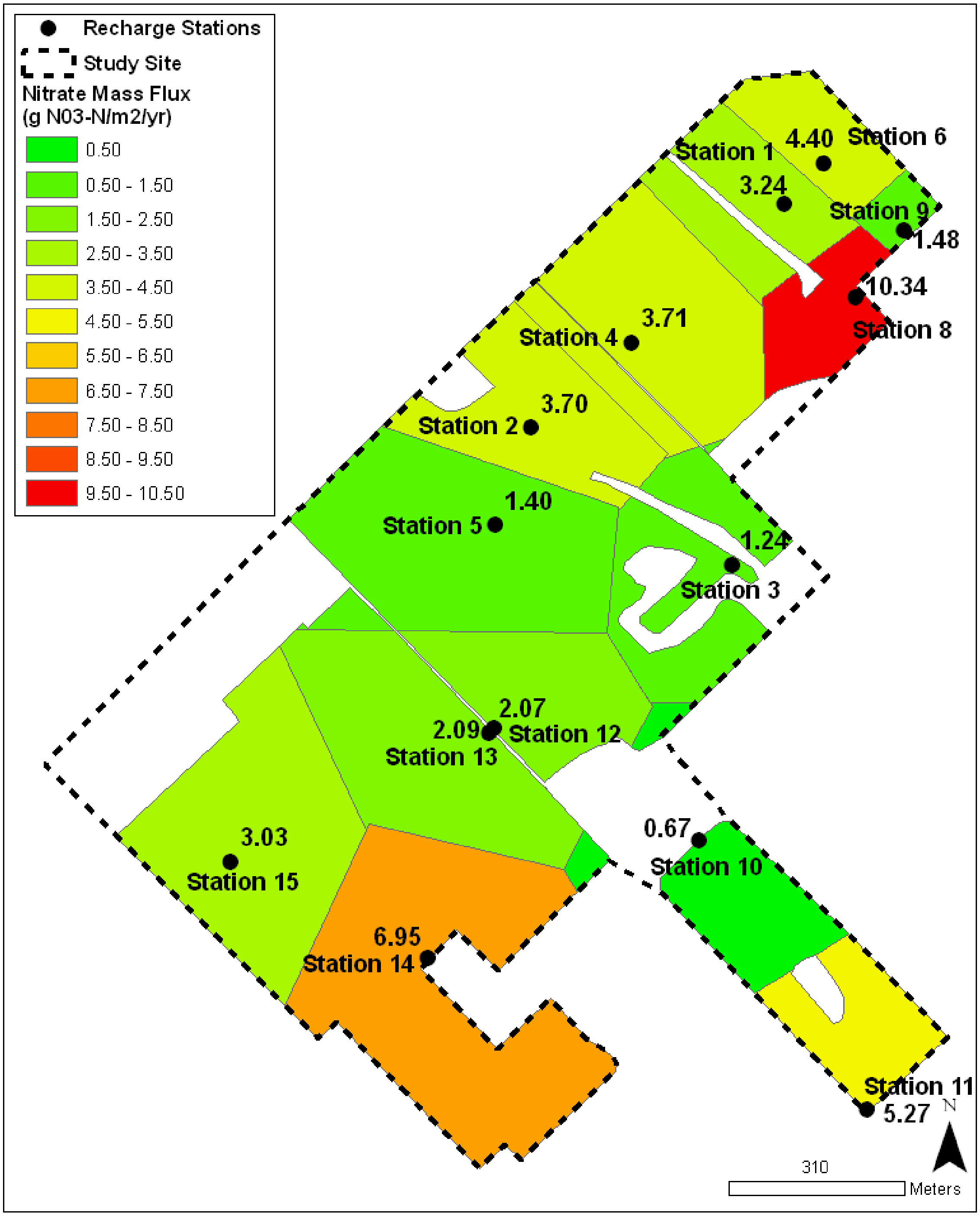


Figure 56. Extropolated nitrate mass flux used to determine nitrate loading using method 3: Thiessen polygons.

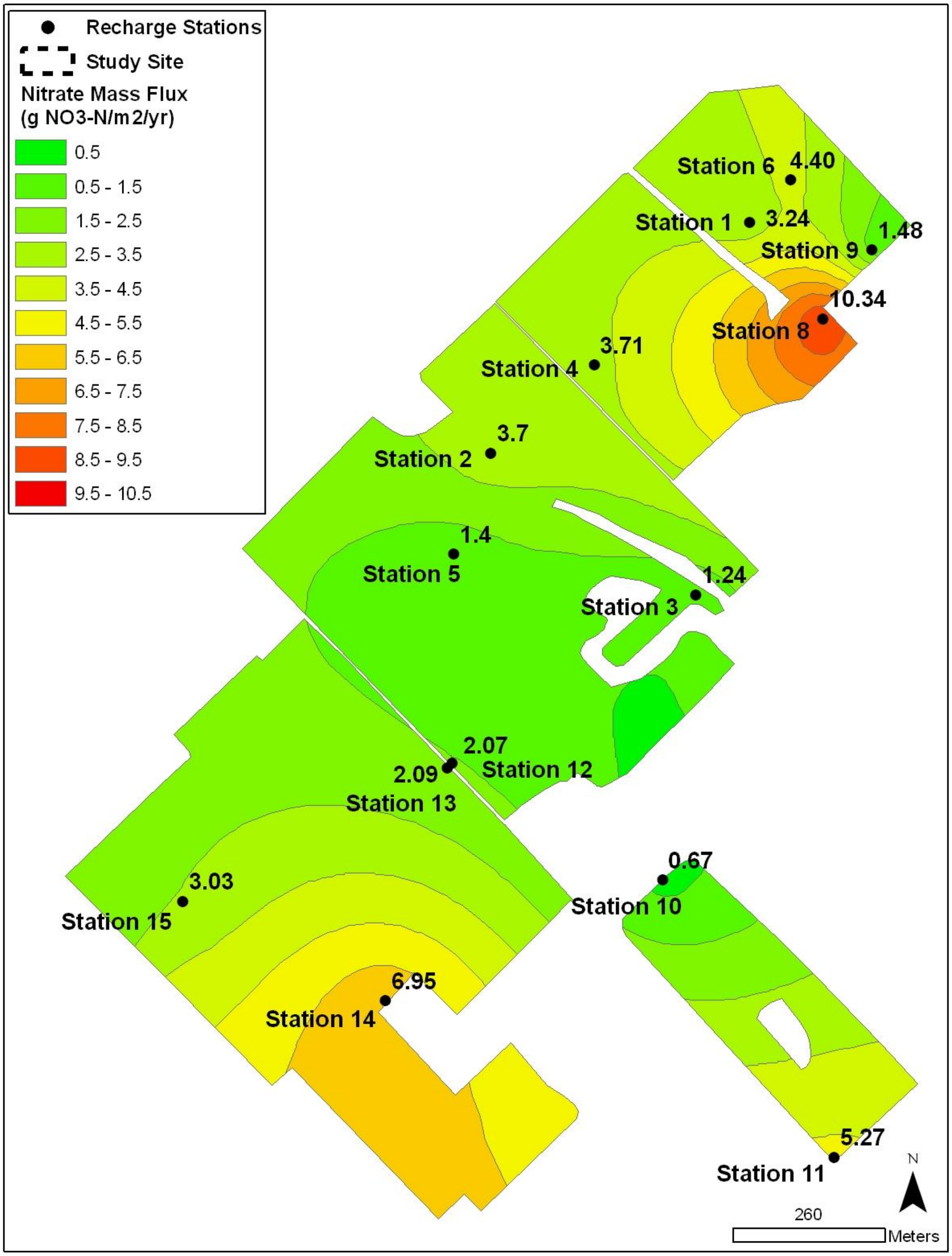


Figure 57. Extrapolated nitrate mass flux used to determine nitrate loading using method 4: Contouring.

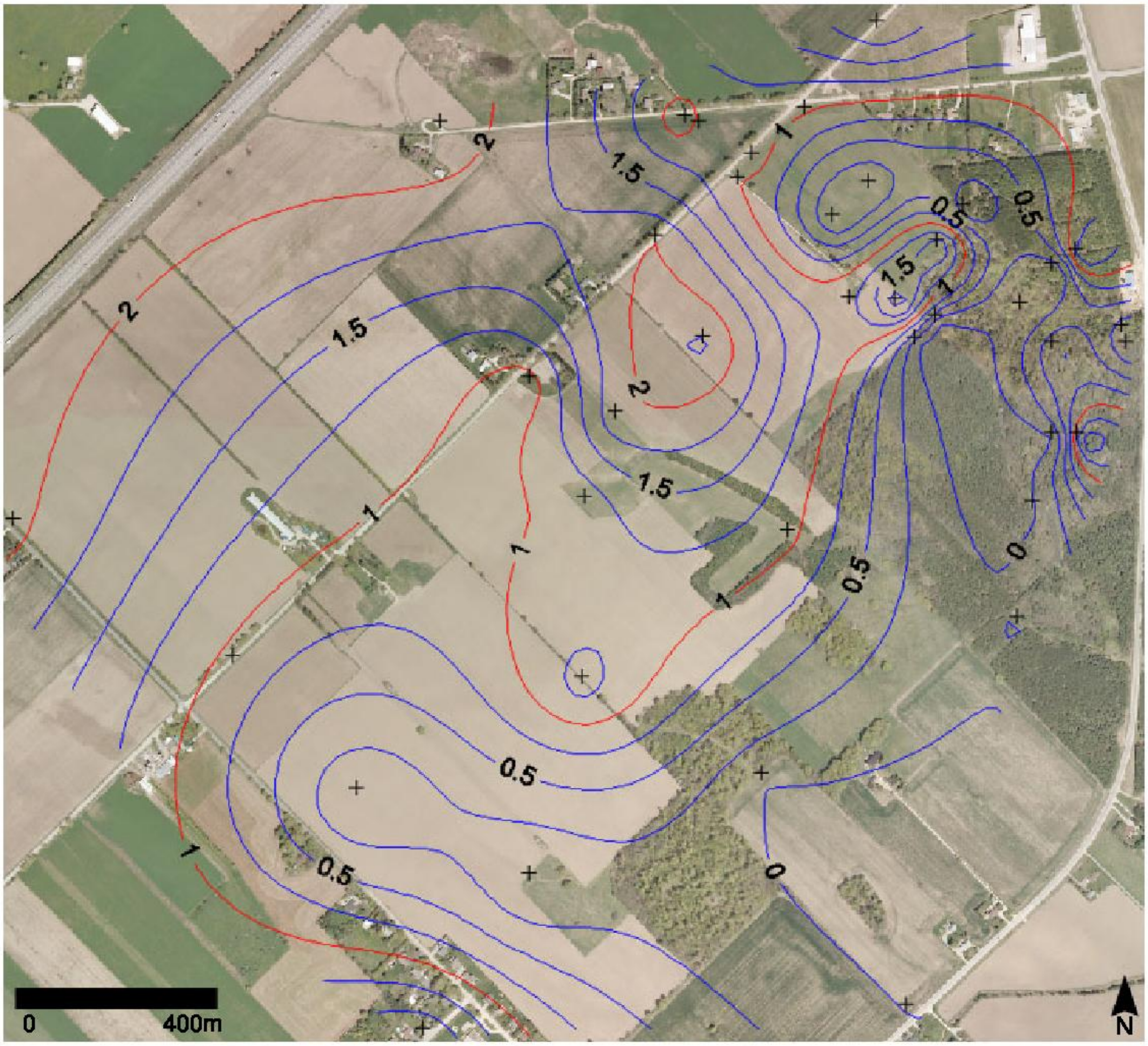


Figure 58. AVI map. Red lines indicate breaks between vulnerability categories (<1, 1-2, and 2-3 which correspond to extremely high, high and moderate vulnerability respectively). Crosses indicate locations where stratigraphic records are available for use in vulnerability calculations.

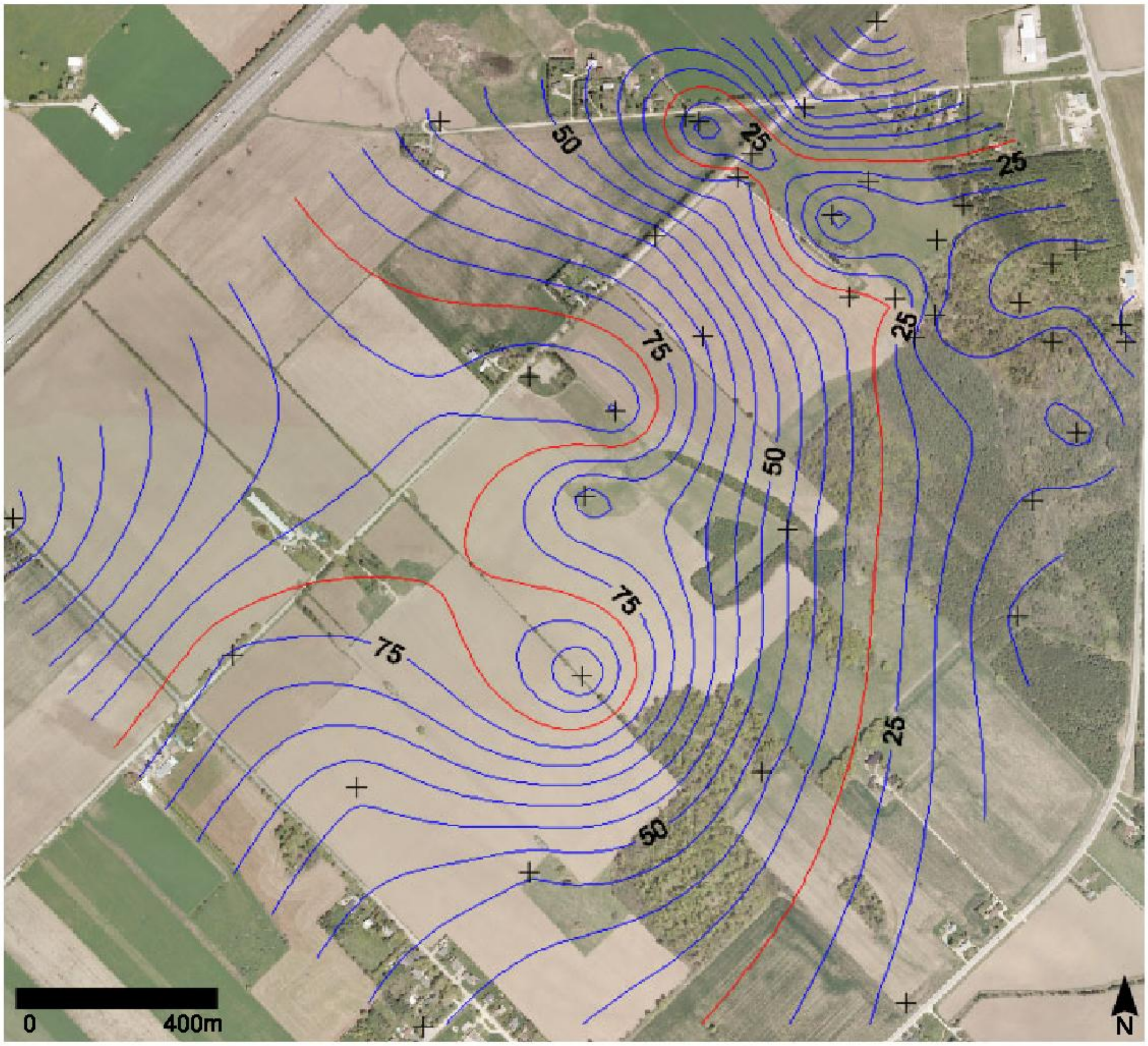


Figure 59. ISI map. Red lines indicate breaks between vulnerability categories (0-30, 30-80, >80 which correspond to high, moderate and low vulnerability respectively). Crosses indicate locations where stratigraphic records are available for use in vulnerability calculations.

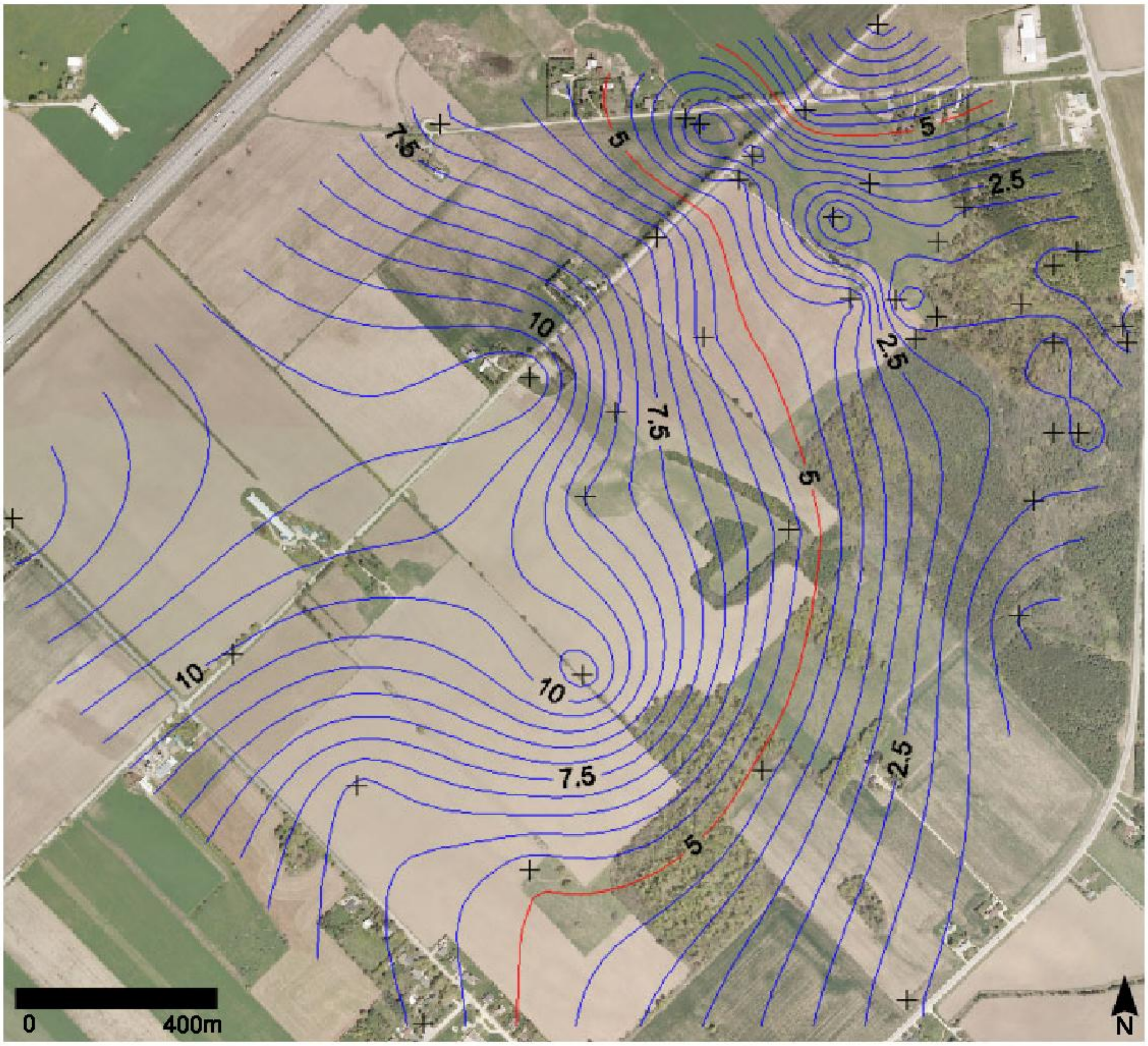


Figure 60. SAAT map. Red lines indicate breaks between vulnerability categories (<5 and 5-25 which correspond to high and moderate vulnerability respectively). Crosses indicate locations where stratigraphic records are available for use in vulnerability calculations.

Chapter 5: Discussion

5.1 Method Benefits and Limitations

The unsaturated zone soil coring and sampling regime utilized in this study produced very positive results. Through periodic coring and sampling, the decreases in nitrate mass in the unsaturated zone and nitrate concentration at the water table due to the BMP were clearly observed. The estimates of nitrate mass loading across the site are very comparable to those approximated at the same site by Bekeris (2007) and Haslauer (2005), as well as under similar conditions by Cole (2008).

The comparison of vulnerability assessment techniques to the pressure and temperature data is very unique and may have a great potential for future use. The use of transducers to capture temperature and pressure fluctuations, especially during highly vulnerable melt water events, may provide a fairly easy and unique method to update and validate results from standard vulnerability assessment techniques. These standard techniques, such as AVI, ISI and SAAT, lack in field verification, which can be provided using the temperature and pressure technique. Furthermore, hydrological inputs, which this study has shown to play an integral role in vulnerability ranking can be incorporated into the vulnerability assessment.

There are several potential sources of error and uncertainty that can result from using the soil coring technique. Poor vertical interpolation of geology can be the outcome of low recovery of soil in the cores or inability to core the full thickness of the unsaturated zone. Laboratory extraction errors or poor QA/QC can be sources of error. Difficulties can also arise from heterogeneities in the subsurface, topography or weather, events which can lead to significant spatial and temporal variations in recharge estimates.

In order to estimate nitrate mass flux, this study applied several simplifications and assumptions, which must be considered. One of these simplifications was that any nitrate transformation processes within the top 1.0 m of the subsurface were ignored. As described in Section 3.3.7, in the root zone of the highly organic shallow subsurface, the fate of nitrogen is subject to a range of transformation processes which may include mineralization, nitrification and denitrification. The parameter of interest in this study was nitrate mass loading to the water table. The detailed investigations of soil characteristics and crop growth necessary to accurately account for the effects of the nitrogen cycle on the mass load estimates would be extremely difficult as these effects would be constantly changing with weather and crop growth and thus were beyond the scope of this study. Therefore, nitrate mass and concentrations within the top 1.0 m of the subsurface were completely disregarded.

A key assumption in the nitrate mass load estimations was that flow in the unsaturated zone was one-dimensional, vertical flow. It was assumed that all recharging water flowed downward in a spatially uniform manner across the study site. This assumption was applied in the estimation of groundwater recharge using the bromide tracer method. Changes in the centre of bromide mass depth were attributed to one-dimensional downward flow and were assumed to represent the movement of water directly beneath the 3 by 3 m bromide test area. Likewise, decreases in soil water storage beneath the ET/drainage boundary were considered to be due to downward groundwater recharge. However, bromide mass losses between tracer application in January 2008 and the subsequent coring event in May 2008 (see Table 11) indicate that non-vertical flow may have been substantial at some stations. This is particularly true in the topographically low-lying areas where ephemeral melt water streams flowed. Additionally, preferential flow pathways, geologic heterogeneities and dispersion processes likely affected unsaturated flow and transport which may have violated the assumption of exclusively vertical flow.

5.2 Effectiveness of BMPs

The monitoring of the unsaturated zone through coring and sampling has shown that the BMP is effectively reducing nitrate mass beneath the agricultural land at the study site. Standard monitoring wells were not able to detect this improvement in the groundwater due to the mixing of smaller volumes of cleaner recharging water with large quantities of nitrate laden aquifer water. This delay in improved groundwater quality is increased by the time lag associated with BMP implementation and the time required for clean water to recharge through the variably thick unsaturated zone and reach the water table. The CMT wells indicate improving conditions. The lower nitrate mass in the unsaturated zone will flush through and the nitrate laden aquifer will become greatly diluted with this cleaner recharging water. It is expected that over the long term, nitrogen cycling in the root zone and heterogeneities in the subsurface will gradually be smoothed out and nitrate concentrations will decrease in the aquifer and at the supply wells. Overall, it is clear from this study that BMPs are capable of effectively reducing nitrate mass within the unsaturated zone. In the long term, these reductions in land application of nutrients are expected to adequately reduce nitrate concentrations in the aquifer and satisfy the drinking water limit of 10 mg NO_3-N/L at the supply wells.

The results of this study were similar to those of Cole (2008) in which a reduction in N loading to the land surface resulted in a decrease in groundwater nitrate concentrations, both at the water table and within a small glaciofluvial aquifer. However, the effectiveness of the BMP at this study site differs significantly from the results produced by Wassenaar et al. (2006) in which a decade of voluntary nutrient reductions yielded no discernable change in groundwater nitrate concentrations within the highly permeable Abbotsford-Sumas Aquifer. Although the Abbotsford-Suma Aquifer is regional in extent and the study site at the Thornton Well Field is local in extent, the effects of reducing surface nutrient loading should have a similar discernible effect on the nitrate concentrations at the water table. However, it is speculated that due to the voluntary nature of the BMPs, non-compliance of farm operators and the application of commercial fertilizers during groundwater recharge events may be responsible for the sustained high nitrate concentrations in the aquifer Wassenaar et al. (2006). The farm operator of the BMP land parcel in this study abided by the nutrient management plan for the farm and commercial fertilizers were applied in a manner to reduce nutrient run off and leaching.

5.3 Upscaling

The ability to take data from small localized areas and use them to evaluate conditions at a larger scale can be very useful. Upscaling in this manner was completed at the study site in order to assess how the overall loading of nitrate to the water table was being affected by the BMP. This was completed by selecting and installing new stations at which to monitor mass flux which were chosen based on specific criteria related to topography and potential for run-on/run-off, near surface geology and recharge. Successful upscaling can be determined by comparing estimates of nitrate mass loading at the newly selected area to the original area where the new area was predicted to have similar characteristics.

While the average, classification, Thiessen polygons and contouring extrapolation methods produced similar results at this field site, further upscaling efforts may produce the most representative results using the classification approach. This technique requires near surface geology, as it is considered to exert a primary control on the accuracy of the upscaling approach. Soil coring to depths of at least 2 mbgs should be completed in as many locations as deemed necessary. The more cores that are collected, the less one must rely upon extrapolative geology over large areas, which can be quite variable such as in this study's glacial moraine environment. Soil coring could greatly aid the upscaling effort by providing a detailed near surface geologic record. Quaternary geology maps may be utilized to aid in the process of selecting where to core and how many cores to collect as these maps can identify where soil types boundaries may lie. If budget allows, coring to the water table would enhance upscaling accuracy and also provide a baseline for unsaturated zone soil conditions. Topographical designations are also required in the classification approach. These data can be acquired using a topographical map but a digital elevation map (DEM) may be used in conjunction with a GIS-based computer program to provide a more integrated result. A GIS program would offer much greater insight into potential for run-on/off which is an integral part of the accuracy of the upscaling process. This process of upscaling using the classification approach is a fairly simple method that can be used to calibrate and apply model-generated estimates of recharge and mass loading at a regional scale.

5.4 Vulnerability

When determining the vulnerability to contamination of a well field or other site of interest, the outcome can have wide reaching effects. Therefore, it is very important that all of the factors that might affect the outcome of the vulnerability assessment be accurately incorporated into the assessment method. As this study has determined, the AVI, ISI and SAAT vulnerability assessment techniques produced fairly similar results. However, the key element missing from the AVI and ISI and lacking from the SAAT methods is hydrology. Temperature and pressure monitoring, especially within key, low-lying areas can be effectively used to monitor hydrological inputs and verify and revise vulnerability assessments. In addition to a singular temperature measurement point such as within a levelogger, temperature profiles from the surface to the water table can be monitored using temperature probes that can be placed in a series down the length of a monitoring well. Such devices can greatly aid tracking the movement of cold melt water as it recharges into the subsurface. This cold temperature front acts as a tracer and can be used to estimate recharge rates. It can also be used at locations to determine whether short circuiting is occurring due to inadequacies in the well construction, which may prove useful at this study site.

5.5 Application of Approach to other Study Sites

The nitrate mass load estimation method described in this study could be utilized at any agricultural site to evaluate the effect of a BMP or to quantify the mass load through the unsaturated zone. These methods proved effective in this study and are recommended for future use at other sites of interest. Ideal sites may include agricultural land areas where coring and sampling can quantify the early, near surface decreases in nitrate mass due to BMPs. These decreases can be easily identified when compared to the higher nitrate mass stored in the unsaturated zone from legacy nitrogen application.

Mass load calculations can be also be used to identify and evaluate trends of other contaminants at other, non-agricultural settings. Other conservative contaminants like chloride may be good candidates for these mass load estimation methods because they would not be subject to conversion processes. However, any mass load calculations would still require hydrological inputs and assumptions involving the nature of groundwater flow within the unsaturated zone.

The method of utilizing temperature and pressure data to verify and improve standard vulnerability assessment techniques can provide valuable insight into determining how vulnerability at a study site varies spatially and specifically temporally. The physical nature of groundwater temperature and pressure can help take into account the influential role of hydrological inputs on vulnerability, which is greatly lacking the AVI, ISI and even SAAT vulnerability assessment techniques.

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

Numerous years of agricultural BMP implementation within the capture zone of the Thornton Well Field has produced interesting and positive results. Stored nitrate mass and porewater nitrate concentrations within the unsaturated zone have decreased steadily leading to significant reductions in nitrate mass flux and loading to the water table. In the last several years, nitrate concentrations within most monitoring wells across the network have ceased to increase and have remained fairly constant. The long screens that exist within many of the monitoring wells allow mixing of cleaner recharging water with older, more contaminated formation water. As such, a significant lag time exists between changing land use practices at the surface and considerable decreases in nitrate concentrations at the supply wells. Nitrate concentrations monitored at the multilevel wells that utilize discrete sampling ports have displayed very low concentrations in the ports nearest the surface which gradually become higher with depth and thus mixing with contaminated formation water.

Measurements which were primarily gathered at 14 locations revealed considerable spatial variability in porewater nitrate concentrations and recharge rate. Average porewater nitrate concentrations at locations located within Parcel B where BMPs were implemented decreased most rapidly where the near surface stratigraphy was sand and gravel. Yearly recharge estimations were hampered due to the lack of a full year of bromide tracer data and high precipitation during the bromide period. Water balance recharge rate estimates which included crop effects but neglected critical inputs such as geology and topography were useful in scaling bromide tracer recharge estimations to a full year rate.

Accurately predicting what conditions may be like outside the area of study can be very useful. This process of upscaling point measurements was tested and revised as an increased amount of information was acquired. Of topography, recharge and near surface geology, the latter is considered to exert the greatest influence. Four methods of interpolating between mass flux point estimates to calculate nitrate mass loading were tested. In this situation where there were several point location estimates, the best approach was the average method due to its simplicity. The other 3 methods only varied from the average method by a maximum 11 %. Using this averaging method, nitrate mass loading estimates within the BMP activated land Parcel B decreased from 2006 to 2008 by 62%. This reduction correlates fairly well with the BMP induced 46% decrease in applied fertilizer within Parcel B.

The vulnerability of the water table to contamination at the site was evaluated using three methods. Overall, the AVI approach assessed vulnerability to be extremely high to high while both the ISI and SAAT approach evaluated the vulnerability to be high to moderate. The travel times calculated by the SAAT approach suggest that surface contaminants would take between thirteen to less than one year to reach the water table. The results from analyzing the temperature and pressure data collected from pressure transducers within wells across the site during snow melt events suggest that there may be regions where vulnerability may be extremely high during such extreme weather events. Such physically measured, temporally dependent data are recommended to use verify and revise the results from standardized vulnerability assessment techniques.

6.2 Recommendations

Due to the positive results at the study site, the following recommendations should be considered.

-Due to the first significant changes in nitrate concentration being recognized in multilevel wells that were discretely screened close to the water table, any further monitoring well installations should strongly consider these types of wells.

-Groundwater monitoring at all locations, especially at the multi level wells, should be continued in order to better characterize the effects of BMP implementation.

-Continued BMP implementation within Parcel B and initiation within Parcel A.

-Continued tracking of bromide tracer is recommended in order to acquire a full year recharge estimation without needing to rely on water balance estimates for scaling purposes.

-Steps to protect highly vulnerable areas during spring melt events need to be considered. Temperature profiles as well as pressure should be monitored in these areas.

-Geologic coring to determine the near surface geology and DEM data should be integrated to accompany efforts to upscale point measurements of nitrate mass flux.

- The average method of interpolating between point nitrate mass flux estimates is suggested when determining nitrate mass loading. This may accompany a 3-D modeling study as nitrate loading estimates are upscaled from the field scale.

Bibliography

Addiscott, T. M., 2004. *Nitrate, Agriculture and the Environment*. Wallingford, UK: CABI Publishing.

Allen, R.G., L. S. Pereira, D. Raes and M. Smith, 1998. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements - Irrigation and Drainage Paper 56*. Rome: Food and Agriculture Organization, United Nations.

Aller, L., T. Bennett, J.H. Lehr, R. Petty and G. Hackett, 1987. *DRASTIC: A Standardized System for Evaluating Groundwater Potential using Hydrogeological Settings*: NWWA/U.S. EPA Report 600/2-85-018

Almasri, M. N. and Jagath J. Kaluarachchi, 2005. Multi-criteria Decision Analysis for the Optimal Management of Nitrate Contamination of Aquifers. *J. Environmental Management*. 74: 365-381

American Society for Testing and Materials, 2005. *D2216-05, Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass.*

American Society for Testing and Materials, 2006. *D2487-06, Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System).*

ASTM. See American Society for Testing and Materials.

Bear, J., 1972. *Dynamics of Fluids in Porous Media*. New York: American Elsevier.

Bekeris, L., 2007. *Field-scale Evaluation of Enhanced Agricultural Management Practices using a Novel Unsaturated Zone Nitrate Mass Load Approach.* Master's thesis, University of Waterloo.

Bleifuss, P., 1998. *Tracing Sources of Nitrate in the Long Island Aquifer System*, Master's Thesis, Deptartment of Geosciences, SUNY-SB.

Boumans, L. J. M., B. Fraters, and G. van Drecht, 1999. Nitrate in the Upper Groundwater of "De Marke" and Other Farms. *Netherlands Journal of Agricultural Science.* 49: 163-177.

Brasel, K.E., and D. Reif, 1979. A Procedure to Generate Thiessen Polygons. *Geographical Analysis*. 11: 289–303.

Burkart, M. R., and J. D. Stoner, 2002. Nitrate in Aquifers Beneath Agricultural Systems. *Water Science and Technology*. 45(9): 19-29.

Cole, J., 2008. *Quantification of the Long-term Effects from Nutrient Reductions on Groundwater* Nitrate Concentrations in an Agricultural Setting. Master's thesis, University of Waterloo.

Constantz, J., A.E. Stewart, R. Niswonger, and L. Sarma. 2002. Analysis of Temperature Profiles for Investigating Stream Losses Beneath Ephemeral Channels. *Water Resources Research*, 38(12): 52-1–52-13.

Corporation of the County of Oxford, 1990. Limits. Woodstock, Ontario: The Corporation of the County of Oxford.

Corporation of the County of Oxford, 1994. *Soils*. Woodstock, Ontario: The Corporation of the County of Oxford.

Corporation of the County of Oxford, 2000. *County of Oxford Ortho Imagery*. Woodstock, Ontario: The Corporation of the County of Oxford.

Corporation of the County of Oxford, 2001. *Quaternary Geology*. Woodstock, Ontario: The Corporation of the County of Oxford.

Corporation of the County of Oxford, 2003a. *Wetlands.* Woodstock, Ontario: The Corporation of the County of Oxford.

Corporation of the County of Oxford, 2003b. *Municipal Water Wells*. Woodstock, Ontario: The Corporation of the County of Oxford.

Corporation of the County of Oxford, 2003c. *Roads.* Woodstock, Ontario: The Corporation of the County of Oxford.

Corporation of the County of Oxford, 2003d. *Surface Water Bodies.* Woodstock, Ontario: The Corporation of the County of Oxford.

Corporation of the County of Oxford, 2003e. *Surface Water Channels.* Woodstock, Ontario: The Corporation of the County of Oxford.

Corporation of the County of Oxford, 2003f. *Topography – Contours.* Woodstock, Ontario: The Corporation of the County of Oxford.

Cowan, W. R., 1975. *Quaternary Geology of the Woodstock Area, Southern Ontario: Geological Report 119*. Ontario: Ontario Division of Mines, Ministry of Natural Resources.

Environment Canada, 2008. *National Climate Data and Information Archive: Canadian Climate Normals 1971-2000* accessed February 26, 2008 from electronic source http://www.climate.weatheroffice.ec.gc.ca/climate (http://climate.weatheroffice.ec.gc.ca/climate_normals/results_e.html?Province=ONT%20&StationName=&SearchType=&LocateBy=Province&Proximity=25&ProximityFrom=City&StationNumber=&IDType=MSC&CityName=&ParkName=&LatitudeDegrees=&LatitudeMinutes=&LongitudeDegrees=&LongitudeMinutes=&NormalsClass=A&SelNormals=&StnId=4835&).

European Environment Agency, 2009. *Nutrients in European Ecosystems*, accessed February 7, 2009 from electronic source http://www.eea.europa.eu/publications/ENVIASSRP04/page001.html.

Fertilizer Institute of Ontario Foundation. 2001. *The Next Best Thing to Rain: The History of the Fertilizer Industry in Ontario*. Guelph, Ontario: The Fertilizer Institute of Ontario.

Focazio, M. J., T.E. Reilly, M.G. Rupert, and D.R. Helsel, 2002. *Assessing Ground-Water Vulnerability to Contamination: Providing Scientifically Defensible Information for Decision Makers*. U.S. Department of the Interior: U.S. Geological Survey Circular 1224.

Freeze, R.A., and J.A. Cherry, 1979. *Groundwater*. Englewood Cliffs, New Jersey: Prentice-Hall.

Frind, E.O., J.W. Molson, and D.L. Rudolph, 2006. Well Vulnerability: A Quantitative Approach for Source Water Protection. *Ground Water,* 44(5): 732–742.

Fujiwara, N., T. Osanai, T. Kamada, T. Katoh, K. Takahashi and K. Okumura, 2000. Study on the Relationship between Plasma Nitrite and Nitrate Level and Salt Sensitivity in Human Hypertension, *Circulation: Journal of the American Heart Association*, 101:856-861.

Gierczak, R., J.F. Devlin, D.L. Rudolph, 2007. Field Test of a Cross-injection Scheme for Stimulating in situ Denitrification Near a Municipal Water Supply Well. *Journal of Contaminant Hydrology* 89: 48–70.

Greacen, E. L., B. L. Correll, R. B. Cunningham, G. G. Johns, and K. D. Nicolls, 1981. Calibration. In E.L. Greacen (Ed.) *Soil water assessment by the neutron method* (pp. 50-81). East Melbourne, Australia: CSIRO.

Golden Software, Inc, 2004. *Surfer version 8.05*. Golden, Colorado.

Goss, M.J., D.A.J. Barry, and D.L. Rudolph, 1998. Contamination in Ontario Farmsted Domestic Wells and its Association with Agriculture: 1. Results from Drinking Water Wells. *Journal of Contaminant Hydrogeology* 32: 267-293.

Gupta S.K., R.C. Gupta, A.B. Gupta, A.K. Seth, J.K. Bassin, and A. Gupta, 2000. Recurrent Acute Respiratory Infections in Areas with High Nitrate Concentrations on Drinking Water. *Environmental Health Perspectives* 108: 363–366.

Haslauer, C.P., 2005. *Hydrogeologic Analysis of a Complex Aquifer System and Impacts of Changes in Agricultural Practices on Nitrate Concentrations in a Municipal Well Field: Woodstock,Ontario*. Master's thesis, University of Waterloo.

Heagle, D.J., 2000. *Nitrate Geochemistry of a Regional Aquifer in an Agricultural Landscape, Woodstock, Ontario.* Master's thesis, University of Waterloo.

Health Canada, 2006. *Guidelines for Canadian Drinking Water Quality Summary Table*. Prepared by the Federal-Provincial-Territorial Committee on Drinking Water.

Hill, M.J., 1999. Nitrate Toxicity: Myth or Reality? *British Journal of Nutrition*, 81(5): 343-344.

Kung, K.J.S., 1990. Influence of Plant Uptake on the Performance of Bromide Tracer. *Soil Science Society of America Journal* 54 (4-6): 975-979.

Lee D.J., and C.S. Kim, 2002. Nonpoint Source Groundwater Pollution and Endogenous Regulatory Policies. *Water Resources Research* 38(12): 11-1 – 11-13.

Manassaram, D.M., L.C. Backer, and D.M. Moll, 2006. A Review of Nitrate in Drinking Water: Maternal Exposure and Adverse Reproductive and Developmental Outcomes. *Environmental Health Perspectives* 114(3): 320-327.

Martinez, Y., and J. Albiac, 2004. Agricultural Pollution Control under Spanish and European Environmental Policies. *Water Resources Research* 40(10): W10501.

McCutcheon, C., 2008. Determination of the Accuracy of the Method and Instrumentation of the Temperature Tracer Study. Work Term Report, University of Waterloo.

McMahon, P.B., K.F. Dennehy, B.W. Bruce, J.K. Böhlke, R.L. Michel, J.J. Gurdak, and D.B. Hurlbut, 2006. Storage and Transit Time of Chemicals in Thick Unsaturated Zones under Rangeland and Irrigated Cropland, High Plain, United States. *Water Resources Research* 42: W03413.

Nutrient Management Act, 2002. S.O. 2002, c.4.

OMAF. See Ontario Ministry of Agriculture and Food Agriculture Canada.

Ontario Ministry of Agriculture and Food and Agriculture Canada, 1994. *Nutrient Management-Best Management Practices*. Ontario: Ontario Ministry of Agriculture and Food.

Ontario Ministry of Environment, 2006. Assessment Report: Draft Guidance Module 3 - Groundwater Vulnerability Analysis (for use with source protection technical studies). Ontario: Ontario Ministry of Environment.

Padusenko, G., 2001. Regional Hydrogeologic Evaluation of a Complex Glacial Aquifer System in an Agricultural Landscape: Implications for Nitrate Distribution. Master's thesis, University of Waterloo.

Rahman, R., 2008. On the Implications of Various Approaches to Groundwater Source Protection. PhD thesis, University of Waterloo.

Rudolph, D.L., D.A.J. Barry, and M.J. Goss, 1998. Contamination in Ontario Farmsted Domestic Wells and its Association with Agriculture: 2. Results from Multilevel Monitoring Well Installations. Journal of Contaminant Hydrogeology 32: 295-311.

Scanlon, B. R., D. G. Levitt, K. E. Keese, R. C. Reedy, and M. J. Sully, 2005. Ecological Controls on Water-Cycle Response to Climate Variability in Deserts. *Proceedings of the National Academy of Sciences* 102:6033–6038.

Scanlon, B.R., R.W. Healy, and P.G. Cook, 2002. Choosing Appropriate Techniques for Quantifying Groundwater Recharge. *Hydrogeology Journal* 10:18-39.

Schmidt, R.R., 1987. *Groundwater Contamination Susceptibility in Wisconsin: Wisconsin's Groundwater Management Plan Report*. Madison, Wisconsin: Wisconsin Department of Natural Resources (PUBL-WR-177-87).

Smith, S. D., T. E. Huxman, S. F. Zitzer, T. N. Charlet, D. C. Housman, J. S. Coleman, L. K. Fenstermaker, J. R. Seemann, and R. S. Nowak, 2000. Elevated CO_2 Increases Productivity and Invasive Species Success in an Arid Ecosystem. *Nature*, 408:79–82.

Soil Resource Group, 2006. *Agronomic Services for County of Oxford Lands within the Thornton Well Field*. Ontario: Final Report, Soil Resource Group.

Spalding, R. F., M. E. Exner, C. W. Lindau, and D. W. Eaton, 1982. Investigation of Sources of Groundwater Nitrate Contamination in the Burbank-Wallula Area of Washington, U.S.A. *Journal of Hydrology* 58: 307-324.

Squillace, P. J., J.C. Scott, M.J. Moran, B.T. Nolan, and D.W. Kolpin, 2002. VOCs, Pesticides, Nitrate, and their Mixtures in Groundwater used for Drinking Water in the United States. Environmental Science and Technology 36: 1923-1930.

Tomer, M. D., and M. R. Burkart, 2003. Long-term Effects of Nitrogen Fertilizer use on Groundwater Nitrate in Two Small Watersheds. *Journal of Environmental Quality* 32: 2158-2171.

Trotta, L. C., 1985. The Potential for Contamination of Groundwater Based on Hydrogeology: A Geographical Information System Application. In *Annual Midwest Groundwater Conference, St. Paul, Minnesota: October 23-25* (Abstract).

U.S. Environmental Protection Agency, 1987. *Guidelines for Delineation of Wellhead Protection Areas*. Office of Water, Report EPA-4405-93-001.

U.S. Environmental Protection Agency, 1997. *State Source Water Assessment and Protection Program Guidance: Final Guidance*. Office of Water, Report EPA 816-R-97-009.

Van Stempvoort, D. R., D.L. Ewert, and L. Wassenaar, 1992. *AVI: A method for Groundwater Protection Mapping in the Prairie Provinces of Canada.* Regina, Saskatchewan: Prairie Provinces Water Board Report 114.

Wassenaar, L. I., M. J. Hendry, and N. Harrington, 2006. Decadal Geochemical and Isotopic Trends for Nitrate in a Transboundary Aquifer and Implications for Agricultural Beneficial Management Practices. *Environmental Science and Technology* 40:4626-4632.

Wicklund, R. E., and N. R. Richards, 1961. *The Soil Survey of Oxford County: Report No. 28*. Ontario: Ontario Soil Survey, Research Branch, Canada Department of Agriculture and the Ontario Agricultural College.

Wolfe, A.H., and J.A. Patz, 2002. Reactive Nitrogen and Human Health: Acute and Long-term Implications. *Royal Swedish Academy of Sciences* 31(2): 120-125.

Yao, T., P. Wierenga, A. Graham, and S. Neuman, 2004. Neutron Probe Calibration in a Vertically Stratified Vadose Zone. *Vadose Zone Journal* 3:1400-1406.

Appendix A: Evapotranspiration Parameters and Calculation

The following calculation is based upon a method described by Allen et al. (1998) and is a modified version of text excerpted from Appendix C of Bekeris (2007). Bekeris (2007) also provided the author with a Microsoft Excel (MS Excel) spreadsheet containing the formulas listed below (unpublished). This spreadsheet was later modified to characterize the site-specific conditions of this study.

Reference evapotranspiration is expressed by the following:

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$$

Where,

ET_o	reference evapotranspiration [mm day^{-1}]
R_n	net radiation at the crop surface [MJ m^{-2} day^{-1}]
G	soil heat flux density [MJ m^{-2} day^{-1}]
T	air temperature at 2 m height [°C]
u_2	wind speed at 2 m height [m s^{-1}]
e_s	saturation vapour pressure [kPa]
e_a	actual vapour pressure [kPa]
$e_s - e_a$	saturation vapour pressure deficit [kPa]
Δ	slope vapour pressure curve [kPa °C^{-1}]
γ	psychrometric constant [kPa °C^{-1}]

Saturation vapour pressure is expressed as:

$$e_s = 0.3054\left[\exp\left(\frac{17.27\,T_{max}}{T_{max} + 237.3}\right) + \exp\left(\frac{17.27\,T_{min}}{T_{min} + 237.3}\right)\right]$$

Where,

e_s	saturation vapour pressure [kPa]
T_{max}	maximum temperature in daily period [°C]

T_{min} minimum temperature in daily period [°C]

Slope of vapour pressure curve is expressed as:

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2}$$

Where,

Δ slope vapour pressure curve [kPa °C^{-1}]

T mean air temperature [°C]

Actual vapour pressure is expressed as:

$$e_a = \frac{\exp\left(\frac{17.27T_{\min}}{T_{\min}+237.3}\right)\frac{RH_{\max}}{100} + \exp\left(\frac{17.27T_{\max}}{T_{\max}+237.3}\right)\frac{RH_{\min}}{100}}{2}$$

Where,

e_a actual vapour pressure [kPa]

T_{max} maximum temperature in daily period [°C]

T_{min} minimum temperature in daily period [°C]

RH_{max} maximum relative humidity in daily period [%]

RH_{min} minimum relative humidity in daily period [%]

Psychrometric constant is expressed as :

$$\gamma = 0.665 \cdot 10^{-3}\, P$$

Where,

γ psychrometric constant [kPa °C^{-1}]

P atmospheric pressure [kPa]

Net radiation is expressed as:

$$R_n = R_{ns} - R_{nl}$$

Where,

R_n	net radiation [MJ m^{-2} day^{-1}]
R_{ns}	incoming net shortwave radiation [MJ m^{-2} day^{-1}]
R_n	outgoing net shortwave radiation [MJ m^{-2} day^{-1}]

Net outgoing longwave radiation is expressed as:

$$R_{nl} = \sigma\left[\frac{T_{\max,K}{}^4 + T_{\min,K}{}^4}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right)$$

Where,

R_{nl}	net outgoing longwave radiation [MJ m^{-2} day^{-1}]
σ	Stefan-Boltzmann constant [4.903 x 10^{-9} MJ K^{-4} m^{-2} day^{-1}]
$T_{max,K}$	maximum absolute temperature during the 24-hour period [K]
$T_{min,K}$	minimum absolute temperature during the 24-hour period [K]
e_a	actual vapour pressure [kPa]
R_s	measured or calculated solar radiation [MJ m^{-2} day^{-1}]
R_{so}	calculated clear-sky radiation [MJ m^{-2} day^{-1}]

Calculated clear-sky radiation is expressed as:

$$R_{so} = (0.75 + 2 \cdot 10^{-5} z)\ R_a$$

Where,

z	station elevation above sea level [m]
R_a	extraterrestrial radiation [MJ m^{-2} day^{-1}]

Extraterrestrial radiation is expressed as:

$$R_a = \frac{24 \cdot 60}{\pi} G_{sc} d_r \left[\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s\right]$$

Where,

R_a	extraterrestrial radiation [MJ m^{-2} day^{-1}]
G_{sc}	solar constant [0.0820 MJ m^{-2} day^{-1}]
d_r	inverse relative distance Earth-Sun
ω	sunset hour angle [rad]
φ	latitude [rad]
δ	solar declination [rad]

Inverse relative distance Earth-Sun and solar declination are expressed as:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right)$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right)$$

Where,

J	number of the day in the year

Sunset hour angle is expressed as

$$\omega_s = \arccos[-\tan\varphi \tan\delta]$$

CALCULATION OF CROP EVAPOTRANSPIRATION (ET_c)

$$ET_{c\,adj} = (K_s K_{cb} + K_e) ET_o$$

Where,

$ET_{c\ adj}$	crop evapotranspiration adjusted for soil water stress
K_s	water stress coefficient
K_{cb}	basal crop coefficient
K_e	soil evaporatation coefficient

Three values for K_{cb} are required to describe and construct the crop coefficient curve: those during the initial stage ($K_{cb\ ini}$), the mid-season stage ($K_{cb\ mid}$) and at the end of the late season stage ($K_{c\ end}$).

The following is a sample calculation based upon and partially excerpted from Bekeris (2007):

SAMPLE CALCULATION:

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
	Day	ET_o	P-RO	I/f_w	height	K_{cmax}	f_c	f_w	f_{ew}	K_{cb}	$D_{e,i\ start}$	K_r	K_e	E
1	135	1.350	0	0	0.261	1.186	0.01	1	0.99	0.15	0	1	1.036	1.398
2	136	1.812	0	0	0.261	1.183	0.01	1	0.99	0.15	1.41	1	1.033	1.873

	O	P	Q	R	S	T	U	V	W	X	Y	Z
	DPe	De,i end	Kc	ETc	Root depth	Ending D	Irr. Applied	Drainage	Ks	Kc adj	Corrected Ending D	Etc adj
1	0	1.412	1.186	1.600	0	1.600	0	0	1	1.186	1.600	1.600
2	0	3.303	1.183	2.144	0	3.744	0	0	1	1.183	3.744	2.144

Columns:

A day of year

B reference evapotranspiration [mm]

C precipitation minus runoff [mm]

D net irrigation depth [mm]

E plant height [m]

F maximum K_c immediately following wetting [-]

G effective fraction of soil surface covered by vegetation [-]

H fraction of soil surface wetted by irrigation or precipitation [-]

I exposed and wetted soil fraction [-]

J	basal crop coefficient [-]
K	initial depth of evaporation (depletion) [mm]
L	dimensionless evaporation reduction coefficient [-]
M	soil evaporation coefficient [-]
N	evaporation on day i [mm]
O	deep percolation from evaporating layer [mm]
P	depth of evaporation (depletion) at end of day [mm]
Q	dual crop coefficient [-]
R	crop evapotranspiration, uncorrected for soil water stress [mm]
S	root depth [m]
T	root zone depletion at end of day i (soil water stress correction) [mm]
U	net irrigation depth on day i (soil water stress correction) [mm]
V	deep percolation (soil water stress correction) [mm]
W	dimensionless transpiration reduction factor [-]
X	evapotranspiration coefficient [-]
Y	corrected root zone depletion at end of day i [mm]
Z	final crop evapotranspiration value [mm]

Equations for Row 2:

A	day of year
B	ET_o
C	P - RO
D	Irrigation on day 1/H1
E	max((J2/Kcb mid) x max height, E1)
F	max((1.2+(0.04*(u_2-2)-0.004*(RH_{min}-45))*(E2/3)^0.3),(J2+0.05))
G	max((((J2-$K_{c\ min}$)/($K_{c\ max}$ – $K_{c\ min}$))^(1*0.5E2)), 0.01)
H	1 (no irrigation)
I	min(1-G2, H2)
J	basal crop coefficient, varies with crop growth stage
K	max(P1-C2-D2,0)
L	max(if(K2<REW,1,((TEW-K2)/(TEW-REW))),0)
M	min(L2*(F2-J2),I2*F2)

N	M2 x B2
O	max(C2+D2-P1,0)
P	min(K2-C2-D2+N2/I2+O2,0)
Q	M2 + J2
R	Q2 x B2
S	max(min.root+(max.root-min.root)*(J2-$K_{cb\ ini}$)/($K_{cb\ mid}$ – $K_{cb\ ini}$),0)
T	Y1-C2-U2+R2
U	0 (no irrigation)
V	max(C2+U1-R2-Y1,0)
W	if(T2>RAW,(TAW-T2)/(TAW-RAW),1)
X	W2 x J2 + M2
Y	Y1-C2-U2+X2*B2+V2
Z	X2 x B2

Appendix B: Well Logs

WO67 (Monitoring Well)

Date Drilled: November 14-15, 2006
Drilling Inspector: Joanna Passmore
Drillers: Boart Longyear - SDS Drilling
Method: Rotosonic Mini Sonic Drill Rig 4x6" system
Total Depth of Boring: 36.58m
Depth to water: 12.94mbgs (NAD83) (Measured March 27, 2007)
Ground Elevation: 312.46masl (NAD83)
Top of PVC riser elevation: 313.20m (NAD83)
Location: UTM17 North 4770318.11m, East 519488.27m
Originally Surveyed: March 28, 2007
Survey Corrected: June 22, 2007
Installation: - 2.00" Schedule 40 PVC riser and screen
- holeplug from 12.50mbgs to 14.17mbgs
- screen from 15.24mbgs to 18.29mbgs
- sand pack from 14.17mbgs to 36.58mbgs
- grout from 0mbgs to 12.50mbgs
Logged By: Geoff Moroz, Jaqueline Kreller
Last Updated: June 25, 2007

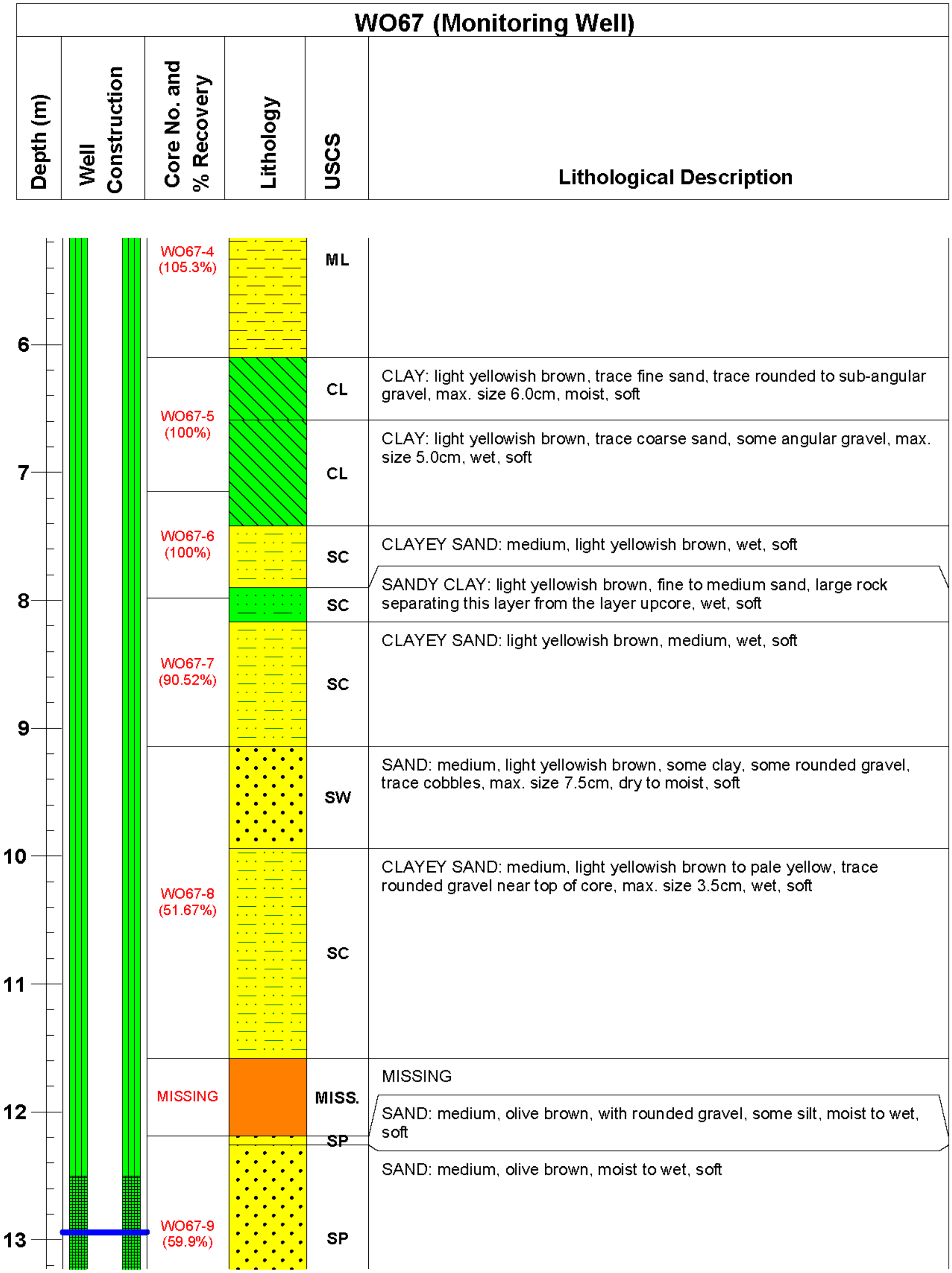
University of Waterloo

USCS = Unified Soil Classification System
mbgs = Metres Below Ground Surface
masl = Metres Above Sea Level

Well Construction Legend:

- Well Screen
- Water Level
- Hole Plug
- Bentonite Grout
- Sand pack

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
0		WO67-1 (78.9%)		Pt	TOPSOIL: dark brown, grading to clayey silt in the next layer, wet, soft, organics
1				CL	CLAYEY SILT: brown, trace coarse sand, trace sub-angular gravel, max. size 3.0cm, wet, soft
		WO67-2 (94.7%)		CL	CLAY: brown, trace coarse sand, trace gravel, trace cobbles, angular to round, max. size 8.0cm, wet, soft
2				CL	CLAY: light yellowish brown, trace medium sand, some silt, trace rounded to angular gravel, max. size 4.0cm, dry to moist downcore, soft
3		WO67-3 (93.4%)		CL	SILTY CLAY: light olive brown, trace sub-rounded gravel, max. size 4.0cm, trace fine sand, dry, firm
4, 5					SILT: light olive brown, some fine sand, some gravel, sub-rounded, some clay, clay content increasing downcore, moist to dry, soft to firm


WO67 (Monitoring Well)
Depth (m)
Well Construction
Core No. and % Recovery
Lithology
USCS
Lithological Description
6
7
8
9
10
11
12
13
WO67-4 (105.3%)
ML
WO67-5 (100%)
CL
CLAY: light yellowish brown, trace fine sand, trace rounded to sub-angular gravel, max. size 6.0cm, moist, soft
CL
CLAY: light yellowish brown, trace coarse sand, some angular gravel, max. size 5.0cm, wet, soft
WO67-6 (100%)
SC
CLAYEY SAND: medium, light yellowish brown, wet, soft
SC
SANDY CLAY: light yellowish brown, fine to medium sand, large rock separating this layer from the layer upcore, wet, soft
WO67-7 (90.52%)
SC
CLAYEY SAND: light yellowish brown, medium, wet, soft
SW
SAND: medium, light yellowish brown, some clay, some rounded gravel, trace cobbles, max. size 7.5cm, dry to moist, soft
WO67-8 (51.67%)
SC
CLAYEY SAND: medium, light yellowish brown to pale yellow, trace rounded gravel near top of core, max. size 3.5cm, wet, soft
MISSING
MISS.
MISSING
SP
SAND: medium, olive brown, with rounded gravel, some silt, moist to wet, soft
WO67-9 (59.9%)
SP
SAND: medium, olive brown, moist to wet, soft

WO67 (Monitoring Well)

Depth (m)	Core No. and % Recovery	USCS	Lithological Description
14	WO67-10 (80.9%)	SP	SAND: medium, olive brown, trace silt, moist to wet, soft
15		SP	SAND: fine, light yellowish brown, some silt, trace gravel, rounded, max. size 6.0cm, wet, soft
	WO67-11 (55.3%)	SP	SAND: medium, light yellowish brown, with silt, moist, soft
16		SM	SILTY SAND: medium, light olive brown, trace clay, with gravel, wetter from 16.04 - 16.23m, soft
17	WO67-12 (103.9%)	SW	CLAYEY GRAVELLY SAND: fine to medium, light yellowish brown, round to sub-angular gravel, max. size 6.5cm, decreasing clay content downcore, moist, soft
		SM-GM	SANDY GRAVELLY SILT: light olive brown, rounded to angular gravel, some cobbles, max. size 9.0cm, fine sand, grading to silty gravelly medium sand by 17.98m, moist, soft
18		GW	SANDY GRAVEL: light yellowish brown, some silt, rounded gravel, all gravel ~1.0cm diameter, moist, loose, grading to clayey gravel by 18.27m
	WO67-13 (113.4%)	ML	SILT: light yellowish brown, some clay, some sub-angular gravel, some fine and coarse sand, dry, firm
19		ML	SILT: light brownish grey, some sub-angular gravel, dry, hard
		CL	SILTY CLAY: light brownish grey, some rounded to sub-angular gravel, trace cobbles, max. size 9.0cm, moist to wet downcore, firm to soft downcore, grades to trace silt downcore, trace fine sand
20		ML	SILT: dark greyish brown, trace clay, some gravel, dry to moist, firm to hard
		ML	SILT: greyish brown, with fine sand, some gravel, trace clay, moist, soft
21		CL	CLAY: light brownish grey, trace medium sand, some silt, trace angular gravel, max. size 2.0cm, dry, hard

WO67 (Monitoring Well)

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
22		WO67-14 (77.8%)		ML	SILT: light brownish grey, with clay, trace fine sand, some to trace gravel, trace cobbles, max. size 8.5cm, trace coarse sand, dry, soft
				CL	SILTY CLAY: light brownish grey, some gravel, trace medium to coarse sand, sub-angular gravel, max. size 2.5cm, moist, soft
23					
24		WO67-15 (171.4%)		CL	CLAYEY SILT: light brownish grey, grading to silty clay downcore, some sub-angular gravel, max. size 5.5cm, trace fine sand, dry to moist in some sections, moister downcore, stiff
25		WO67-16 (100.1%)		CL	CLAYEY SILT: light brownish grey, some fine sand, some gravel (0.5 - 2.5cm diam.), dry and hard from 24.38 to 24.90m, soft and moist to dry for rest of interval
26		WO67-17 (94.5%)		CL	CLAY: grey, trace angular gravel, max. size 2.5cm, trace medium to coarse sand, some silt, moist, hard
27		WO67-18 (114.3%)		CL	CLAY: grey, trace gravel, rounded to angular, max. size 5.0cm, trace fine sand, dry, hard
		WO67-19 (193.3%)		CL	CLAY: grey, trace medium sand, trace angular gravel, max. size 4.0cm, wet, firm to stiff
28		WO67-20 (133.3%)		CL	CLAY: grey, some to trace silt, trace coarse sand, trace angular gravel, max. size 5.5cm, moist, stiff
29				CL	CLAY: grey, trace coarse sand, trace angular gravel, max. size 5.5cm, some silt, firm to stiff

WO67 (Monitoring Well)

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
		WO67-21 (149.3%)		CL	CLAY: grey, some silt, mostly hard crumbly bits (size of coarse sand to small gravel) with a slightly moister matrix, trace gravel, dry, hard
30				CL	CLAY: greyish brown, some silt, some gravel, moist, soft
				CL	CLAY: greyish brown,some gravel, trace silt, dry to moist, hard
31		WO67-22 (95.1%)		ML	SILT: greyish brown, some small gravel, trace clay, moist to dry, firm
32 33		WO67-23 (80.9%)		CL	CLAY: light brownish grey, some silt, some angular gravel, max. size 8.5cm, trace cobbles, trace medium sand, moist, firm
34		WO67-24 (122.0%)		CL	CLAY: light brownish grey, trace medium sand, trace angular gravel, max. size 3.5cm, moist, stiff
35		WO67-25 (94.3%)		CL	CLAY: light brownish grey, some silt, some gravel and cobbles, max. size 10.0cm, moist to dry, stiff
36		WO67-26 (103.3%)		CL	CLAY: grey, trace fine sand, trace angular gravel, max. size 4.0cm, a little broken up, moist, firm

Notes:
- for 5' cores, percent recovery based on a total core length of 1.524m
- developed January 17, 2007 with a Monsoon pump
- pumped water until clear; total water pumped 510L
- well is located on the right side of the road headed south along Curry Rd., right after Old Stage Rd.
- water level measured from top of PVC pipe, stickup: 0.74m

WO68 (Monitoring Well)

University of Waterloo

Date Drilled: November 17-18, 2006
Drilling Inspector: Joanna Passmore, Jason Cole
Drillers: Boart Longyear - SDS Drilling
Method: Rotosonic Mini Sonic Drill rig 4x6" system
Total Depth of Boring: 41.51m
Water Level: 33.36mbgs (NAD83) (Measured April 4, 2007)
Ground Elevation: 334.29masl (NAD83)
Top of PVC riser elevation: 335.20masl (NAD83)
Location: UTM17 North 4770032.89m, East 519231.13m
Originally Surveyed: March 28, 2007
Survey Corrected: June 22, 2007
Installation: - 2.00" Schedule 40 PVC riser and screen
- screen from 36.42mbgs to 39.47mbgs
- sand pack from 35.66mbgs to 41.51mbgs
- liquid grout from 0.76mbgs to 33.52mbgs
Logged By: Geoff Moroz, Jaqueline Kreller
Last Updated: June 25, 2007

USCS = Unified Soil Classification System
masl = Metres Above Sea Level
mbgs = Metres Below Ground Surface

Well Construction Legend:

- Well Screen
- Water Level
- Hole Plug
- Bentonite Grout
- Sand pack

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
0		WO68-1a, 40.03% of 1.524m		Pt	TOPSOIL: dark brown, moist, lots of organics
				CL	CLAY: reddish brown, with silt, moist
1		WO68-1b, 40.03% of 1.524m		GC	GRAVELLY CLAY: brownish grey, with sand, with silt, moist to wet
				GM	GRAVELLY SILT: brown, with organics, wet (possibly from drill water)
				CL	CLAYEY SILT: brown, moist to wet
2				SM	SILTY SAND: fine, brown, some clay, trace gravel, wet (possibly from drill water)
		WO68-2, 85.30% of 1.524m		GM-GC	SILTY GRAVELLY SAND: coarse, greyish brown, wet, rounded to sub-rounded gravel
3				CL	SILTY GRAVELLY SAND: brown, with sand, wet
				GC	CLAYEY GRAVEL: brown, large range of gravel, max. size 8cm, increasing clay content downwards, moist
4		WO68-3, 90.55% of 1.524m		SM	SILTY GRAVELLY SAND: coarse to medium, brown, sub-rounded to rounded gravel, moist, well graded
		WO68-4a, 104.99% of 0.30m		GM-GC	GRAVELLY CLAY: strong brown, gravelly sandy clay, trace cobbles max. size 9.0cm, moist

WO68 (Monitoring Well)

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
5		WO68-4b, 96.78% of 1.22m		GC	CLAYEY GRAVELLY SAND: greyish brown, sub-rounded to sub-angular, max. size 5.5cm, moist
6				SP	SAND: medium to fine, strong brown, some silt, moist
		WO68-5a, 157.48% of 0.30m		SM	SILTY SAND: fine to medium, yellowish-reddish brown, moist to dry
7		WO68-5b, 86.61% of 1.524m		SM	SILTY SAND: brown, dry to moist
8, 9		WO68-6, 86.94% of 1.22m		SM	SANDY SILT: fine, yellowish brown, dry to moist
		WO68-7a, 86.94% of 0.61m		SM	SILTY SAND: fine, brown, moist
10		WO68-7b, 87.49% of 0.92m		SM	SILTY SAND: fine, brown, grades to sandy silt at 34cm, dry to moist
11		WO68-8, 95.14% of 1.524m		ML	SILT: brown, moist
12				SM	SILTY SAND: fine, brown, moist
		WO68-9a,			SAND: fine, brown, with silt, grading to sandy silt 31cm down, wet to moist

WO68 (Monitoring Well)

Depth (m): 13, 14, 15, 16, 17, 18, 19, 20

Core No. and % Recovery	USCS	Lithological Description
65.62% of 1.524m	SP	
WO68-9b, 65.62% of 1.524m	SM	SILTY SAND: fine, strong brown, moist
WO68-10a, 85.30% of 0.30m	SM	SANDY SILT: greyish brown, some clay, trace gravel, moist to wet (grading to wetter downwards)
WO68-10b, 109.09% of 1.22m	SM	SILT: light brown, some sand, very compact, moist to dry
	SP	SAND: medium, with silt, trace clay, moist to dry
	SP	SAND: medium, with silt, with clay, some gravel, max. 4cm, angular and sub-angular, moist to dry
WO68-11a, 95.14% of 1.22m	SP	SAND: medium, brown, some silt, some chunks of silt (2cm), some chunks of clay at 80cm, moist
WO68-11b, 85.30% 0.61m	SP	SAND: medium to fine, brown, with silt, some silt chunks, moist to dry
WO68-11c, 90.22% of 1.22m	SM	SILTY SAND: medium, brown, dry to moist
	SM	SILTY SAND: medium, greyish brown, dry to moist
WO68-12, 96.46% of 1.524m	SM	SILTY SAND: medium, brown, moist
	SM	SANDY SILT: brown, crumbly chunks, moist
WO68-13a, 131.23% of 0.30m		

WO68 (Monitoring Well)

Depth (m): 21, 22, 23, 24, 25, 26, 27

Core No. and % Recovery	USCS	Lithological Description
WO68-13b, 97.60% of 1.22m	CL	CLAYEY SILT: brown, some fine sand, grades to clayey silt at bottom of interval, moist to wet near bottom
WO68-14a, 78.74% of 0.61m	ML	SILT: brown, with sand, dry to moist
WO68-14b, 60.15% of 0.92m	SM	SILTY SAND: fine, brown, dry to moist
WO68-14c, 76.12% of 1.524m	SM	SILTY SAND: fine, greyish brown, poorly graded, some clay, moist to wet
	SM	SILTY SAND: medium to fine, brown, very compacted from 0-15cm, moist
	SM	SILTY SAND: coarse, brown, with gravel, max. 1.5cm, dry to moist
WO68-15, 35.43% of 3.01m	SM	SILTY SAND: medium, brown, with clay, trace gravel, dry to moist
	SM	SILTY SAND: fine, brown, with gravel, max. size 6cm, dry
	SP	SAND: medium, greyish brown, with silt, moist
	SM	SILTY SAND: medium to fine, greyish brown, moist to wet
		SANDY SILT: greyish brown, with clay, wet

WO68 (Monitoring Well)

Core No. and % Recovery	USCS	Lithological Description
WO68-16, 80.71% of 1.524m	SM	
	SM	SILTY SAND: medium, greyish brown, wet
WO68-17, 81.36% of 1.524m	SM	SANDY SILT: brown, very compact, dry to moist
	SM	SILTY SAND: medium, brown, with gravel, sub-angular to sub-rounded, max. size 1.5cm, dry to moist
	SM	SANDY SILT: coarse, brown, some silt, dry to moist
WO68-18, 104.33% of 1.524m	ML	SILT: whitish grey, some gravel, trace sand, dry
	SW	SAND: coarse, with gravel, some silt, dry
WO68-19, 85.30% of 1.524m	SP	SAND: coarse, brown, with silt, moist
	ML	SILT: brown, blob of clay at 99cm (5cm wide), wet
WO68-20, 58.73% of 1.524mm	ML	SILT: brown, trace sand, dry to moist
	SM	SILTY SAND: medium, brown, some gravel increasing downcore, sub-angular, max grain size 1.5cm, trace clay
	SM	SANDY SILT: greyish brown, with clay, trace gravel, max. size 3.5cm, wet
	SP	SAND: coarse, brown, with silt, wet

Depth (m): 28, 29, 30, 31, 32, 33, 34, 35

WO68 (Monitoring Well)

Depth (m)	Core No. and % Recovery	USCS	Lithological Description
	WO68-21, 58.73% of 1.524m	ML	SILT: brown, with sand, very compact, moist
36		ML	SILT: light brown, some clay, compact, wet
	WO68-22a, 19.4% of 3.048m	SM	SILTY SAND: coarse, brown, with gravel, some clay, max. size 4.0cm, sub-angular to sub-rounded, moist
37		SW	SAND: coarse, strong brown, some silt, some gravel, max. size 1.5cm, sub-rounded, moist
	WO68-22b, 29.5% of 3.048m	SP	SAND: coarse, strong brown, some silt, wet (drillers?)
38, 39	WO68-22c, 32.5% of 3.048m	SM	SILTY SAND: coarse, brown, some clay from 45cm on, trace rounded gravel, max. size 3.0cm
40		SP	SAND: medium to coarse, brown, with silt, grading to siltier and finer grained towards bottom
41		SP	SAND: medium, brown, with silt, tace clay near bottom, moist

Notes:

- for 5' cores, percent recovery based on a total core length of 1.524m
- well developed January 31, 2007 with a Mega Monsoon pump
- pumped water until clear; total water pumped: 225L
- well is located just over the first large hill past Old Stage road, on the left side of Curry road beside 2 pine trees
- water level measured from top of PVC pipe, stickup: 1.10m

WO69 (Monitoring Well)

Date Drilled: November 28, 2006
Drilling Inspector: Joanna Passmore
Drillers: Boart Longyear - SDS Drilling
Method: Rotosonic Mini Sonic Drill Rig 4x6" system
Total Depth of Boring: 32.0m
Depth to water: 25.24mbgs (NAD83) (Measured March 27, 2007)
Ground Elevation: 327.60masl (NAD83)
Top of PVC riser elevation: 328.57m (NAD83)
Location: UTM17 North 4769467.58m, East 518627.50m
Originally Surveyed: March 28, 2007
Survey Corrected: June 22, 2007
Installation: - 2.00" Schedule 40 PVC riser and screen
- screen from 25.908mbgs to 28.956mbgs
- sand pack from 25.603mbgs to 29.566mbgs
- grout from 0mbgs to 24.232mbgs
Logged By: Geoff Moroz, Jaqueline Kreller
Last Updated: June 25, 2007

USCS = Unified Soil Classification System
mbgs = Metres Below Ground Surface
masl = Metres Above Sea Level

Well Construction Legend:

- Well Screen
- Water Level
- Hole Plug
- Bentonite Grout
- Sand pack

Core No. and % Recovery	USCS	Lithological Description
	PT	TOPSOIL: very dark brown, moist, lots of organics
WO69-1, 54.4%	CL	SILTY CLAY: reddish-brown, trace coarse sand, moist
WO69-2, 82.7%	SM-SC	SILTY CLAYEY SAND: grey, with gravel, moist
	CL	CLAYEY SILT: reddish-brown, with some coarse sand, trace organics, wet (potentially from drill water)
WO69-3, 113.19%	CL	CLAYEY SILT: with gravel, some coarse to medium sand, gravel coarsens downwards, some cobbles near bottom, moist
	CL	CLAYEY SILT: brown, rounded gravel, moist

Depth (m): 0, 1, 2, 3, 4

WO69 (Monitoring Well)

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
5		WO69-4, 101.16%		CL	SILTY CLAY: grey, some gravel, dry to moist
				GM	GRAVELLY SILT: light grey, angular gravel, dry
6		WO69-5, 118.11%		GC	SILTY CLAYEY TILL: grey, angular gravel, moist
				SM	SILTY SAND: reddish-brown, coarse sand, with gravel, moist
7		WO69-6, 125.77%		SM	SILTY SAND: coarse sand, with gravel, some clay, moist to wet
				SP	GRAVELLY SAND: brown, coarse sand, with silt, wet
8		WO69-7, 101.71%		GM	GRAVELLY SILT: grey, angular gravel, dry
				GM	GRAVELLY SILT: pink to light reddish-brown (grading downwards to reddish-brown), angular gravel, dry
				GM	GRAVELLY SILT: brown, more rounded gravel, dry
9				SM	SILTY SAND: fine sand, yellowish-brown, some clay, clay content increase downcore, dry
10		WO69-8, 91.86%		SM	SILTY SAND: fine to medium sand, brown, dry to moist
11–12		WO69-9, 91.21%		SP	SAND: fine to medium, with silt, dry

WO69 (Monitoring Well)

Core No. and % Recovery	USCS	Lithological Description
	SP	SAND: medium to coarse, trace silt, moist
WO69-10, 53.15%	SP	SAND: medium to fine, brown, trace silt, moist
WO69-11, 78.74%	SM	SILTY SAND: medium to fine, coarsening upwards, dry
MISSING	-	MISSING
WO69-12, 64.96%	SM	SILTY SAND: fine, brown, trace clay, moist to dry
	CL	SILTY CLAY: brown, trace sand, moist
	SM	SILTY SAND: brown, trace fining upwards, clumps of clayey sand, moist
WO69-13, 89.90%	SP	SAND: medium, brown, trace silt, moist
WO69-14, 083.33%	SP	SAND: fine, brown, with silt, moist to dry

Depth (m): 13, 14, 15, 16, 17, 18, 19

Column headings: Depth (m) | Well Construction | Core No. and % Recovery | Lithology | USCS | Lithological Description

WO69 (Monitoring Well)

Depth (m)	Core No. and % Recovery	USCS	Lithological Description
		ML	SILT: light brown to grey, with clay, wet on outside, moist to dry inside
20	WO69-15, 131.23%	ML	SILT: brown, with clay, some fine sand, wet
21	WO69-16, 99.88%	SM	SILTY SAND: fine, brown, with silt, moist
22	WO69-17, 106.63%	SM	SILTY SAND: fine, brown, with silt, moist
		CL	SILTY CLAY: brown, trace silt, dry
		SC	SANDY CLAY: grey, with gravel, with silt, wet
		CL	CLAY: brown, trace silt, moist
23	WO69-18, 67.26%	SM	SILTY CLAYEY SAND: coarse, light brown, some gravel (fairly rounded, some angular), moist to wet
24		SM	SANDY CLAYEY SILT: grey, with gravel (coarsening downwards), wet
25	WO69-19, 66.44%	CL	SILTY CLAY: grey, with sand, with gravel, moist to wet (water content grading downwards)
26	WO69-20, 76.12%	SM	SILTY SAND: coarse, grey, with gravel, rounded to more angular gravel downwards, moist to wet

WO69 (Monitoring Well)

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
27				SP	SAND: medium, brown, wet
28		WO69-21, 93.18%		SP	SAND: fine to medium, brown, coarsening down, wet
29		WO69-22, 91.21%		SP	SAND: fine, brown, with silt, moist
				CL	SILTY CLAY: brown, wet
30				SP	SAND: coarse, brown, with silt, moist to wet
31, 32		WO69-23, 88.58%		ML	SANDY SILT: grey, less sandy downcore, moist to wet, grades wetter downcore

Notes:
- for 5' cores, percent recovery based on a total core length of 1.524m
- developed January 19, 2007 with a Monsoon pump
- pumped water until clear; total water pumped 270L
- well is the farthest well south on Curry road, 75m before the 2nd intersection of Curry road
- water level measured from top of PVC, stick-up: 0.97m

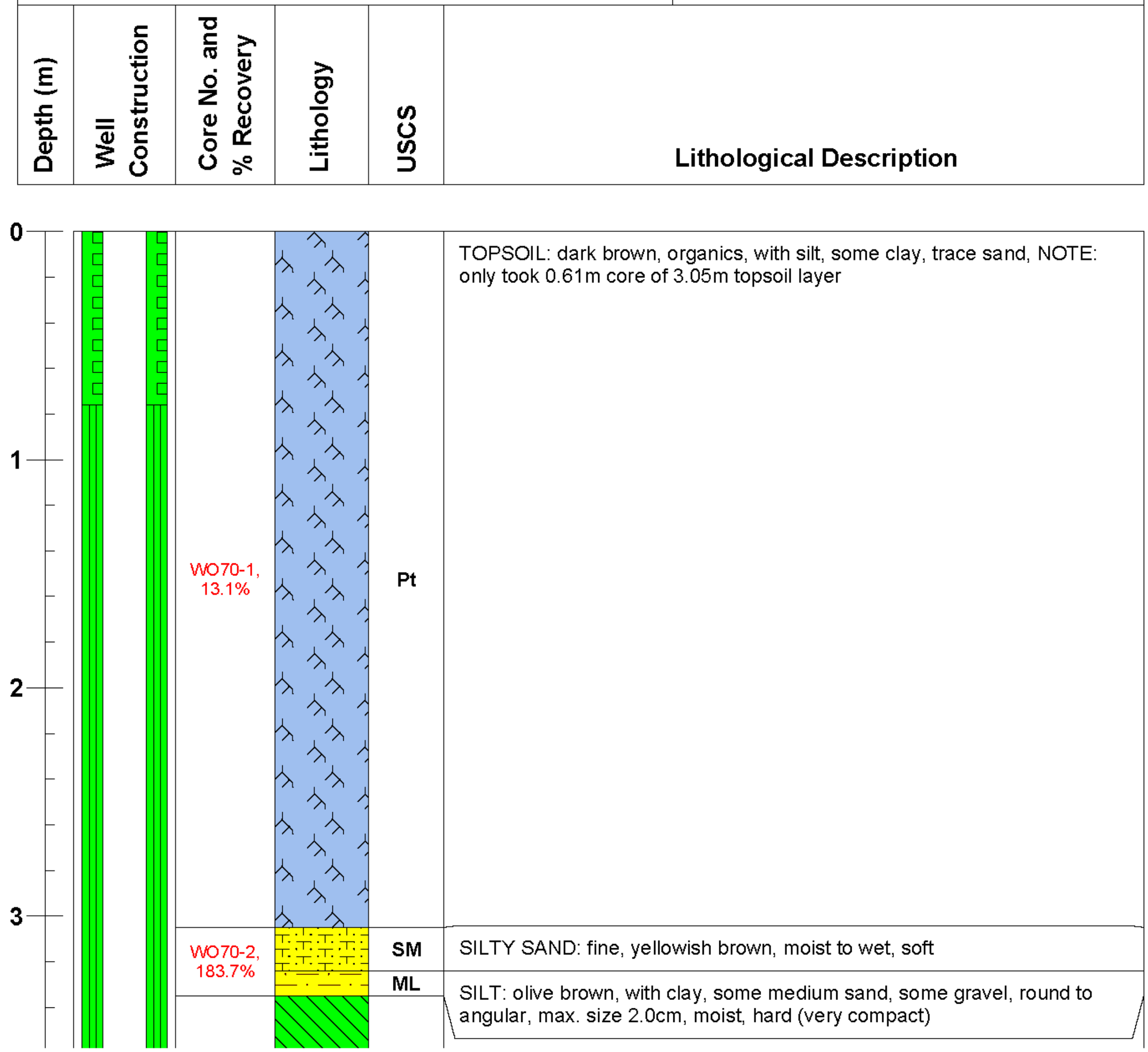
WO70 (Monitoring Well)

University of Waterloo

Date Drilled: December 3-4, 2006
Drilling Inspector: Joanna , Jason Cole
Drillers: Boart Longyear - SDS Drilling
Method: Rotosonic Mini Sonic Drill Rig 4x6" system
Total Depth of Boring: 35.05m
Depth to water: 26.80mbgs (NAD83) (Measured January 11, 2007)
Ground Elevation: 329.36masl (NAD83)
Top of PVC riser elevation: 330.12m (NAD83)
Location: UTM17 North 4769744.76m, East 518180.75m
Originally Surveyed: March 28, 2007
Survey Corrected: June 22, 2007
Installation: - 2.00" Schedule 40 PVC riser and screen
- grout/sand mixture from 0mbgs to 0.76mbgs
- holeplug from 22.40mbgs - 25.76mbgs & 28.96mbgs - 35.05mbgs
- screen from 25.83mbgs to 28.19mbgs
- sand pack from 25.76mbgs to 28.96mbgs
- grout from 0.76mbgs to 22.40mbgs
Logged By: Geoff Moroz, Jaqueline Kreller
Last Updated: June 25, 2007

USCS = Unified Soil Classification System
mbgs = Metres Below Ground Surface
masl = Metres Above Sea Level

Well Construction Legend:
Well Screen; Grout/Sand Mixture; Hole Plug; Water Level; Bentonite Grout; Sand pack



WO70 (Monitoring Well)

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
4		WO70-3, 101.0%		CL	CLAY: olive brown, some coarse sand, some gravel, angular to sub-rounded, max. size 4.0cm, trace silt, black sand lens at 3.63 - 3.64m, slightly less sandy and slightly darker colour downcore, moist, soft to firm
5		WO70-4, 117.3%		CL	CLAY: olive brown, grading from with silt to trace silt downcore, some gravel, rounded, max. size 2.5cm, trace sand, moist, soft
6		WO70-5, 219.8%		CL	CLAYEY SILT: light olive brown, trace angular gravel, max. size 2.0cm, dry to moist, stiff (compact)
7		WO70-6, 115.8%		ML	SILT: light olive brown, some clay, trace gravel, rounded, max. size 3.5cm, slightly more clayey downcore, moist, firm
8		WO70-7, 98.4%		CL	CLAYEY SILT: light olive brown, trace rounded gravel, max. size 1.5cm, less clay grading downcore, moist, soft to firm
9				CL	CLAY: light brownish grey, with silt, some gravel, rounded to angular, max. size 5.0cm, trace coarse sand, moist (wetter downcore), loose, more gravel and sand downcore

WO70 (Monitoring Well)

Depth (m)	Core No. and % Recovery	USCS	Lithological Description
10	WO70-8, 97.8%	SC	SANDY CLAY: light yellowish brown, with rounded to sub-angular, coarse sand, with silt, trace cobbles, max. size 8.0cm, moist to wet, soft to firm, changes to more pinkish yellowish brown at 10.03m, becomes more clayey at 10.39m
11	WO70-9, 121.4%	SC	SANDY CLAY: light yellowish brown to light brownish grey, trace gravel, trace cobbles, max. size 9.5cm, mostly angular gravel, moist (wetter downcore), soft
	WO70-10, 109.4%	GM	GRAVELLY SILT: pale brown to light grey, sub-angular, max. size 7.0cm, dry, loose
		CL	SILTY CLAY: pale brown to light grey, some coarse sand, trace gravel, max. size 2.0cm, wet, soft
		SM	SILTY SAND: fine, olive brown, trace clay, dry to moist, soft
12		CL	SILTY CLAY: pale brown to light grey, moist, soft to firm
	WO70-11, 93.0%	SM	SILTY SAND: fine, brown, poorly graded, moist to wet, soft
		SM	SANDY SILT: pale brown to light yellowish brown, fine sand, very wet, loose
13	WO70-12, 129.6%	SP	SAND: fine, brown, some silt, poorly graded, moist, soft
		SM	SANDY SILT: light yellowish brown, grading, angular to rounded, max. size 3.0cm, changes to gravelly silt by 13.64m, max. size 10.0cm, angular, some clay, moist, soft to firm
14		ML	SILT: light yellowish brown, some to trace coarse sand, trace gravel, rounded to angular, max. size 7.0cm, dry to moist, soft to firm
	WO70-13, 75.4%		SANDY SILT: pale brown, some clay at top grading to no clay at bottom, trace rounded to angular gravel, max. size 6.5cm, dry, soft

Column headings printed on the log: Depth (m), Well Construction, Core No. and % Recovery, Lithology, USCS, Lithological Description.

WO70 (Monitoring Well)

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
15				SM	
		WO70-14, 82.0%		SP	SAND: fine, light yellowish brown, some silt, dry, poorly graded, soft
16					
17		WO70-15, 85.3%		SP	SAND: fine, light yellowish brown, some silt, dry, poorly graded, some chunks of silt from 17.12 - 17.55m, soft, firm from 17.12 - 17.55m
18		WO70-16, 203.4%		SP	SAND: fine, light yellowish brown, trace silt, dry to moist, poorly graded, soft
				SP	SAND: fine to medium, brown, trace silt, dry (moist downcore), poorly graded, soft
19		WO70-17, 118.1%		SM	SILTY SAND: fine, light yellowish brown, dry (moist downcore), some silt chunks, soft
20		WO70-18			SANDY SILT: brown, fine sand, wet, soft

WO70 (Monitoring Well)

Depth (m)	Core No. and % Recovery	USCS	Lithological Description
	WO70-18, 131.2%	SM	
	WO70-19, 115.6%	ML	SILT: light olive brown, trace sand, trace clay, trace gravel, max. size 2.5cm, rounded, dry to moist, soft to firm
21		ML	SILT: light yellowish brown to light brownish grey, with gravel, rounded to angular, max. size 3.0cm, trace clay, dry, soft to firm
		ML	SILT: light yellowish brown to light brownish grey, with gravel, rounded to angular, max. size 7.0cm, silt in large hard angular chunks, dry, stiff
22	WO70-20, 108.3%	ML	SILT: light yellowish brown, trace gravel, rounded, max. size 2.0cm, dry, firm
23	WO70-21, 97.3%	SC	SANDY CLAY: very pale brown, some gravel, rounded to sub-rounded, max. size 6.0cm, coarse sand, moist to wet, loose
		GC	CLAYEY GRAVEL: pale brown, angular, trace coarse sand, trace cobbles, max. size 8.5cm, wet, loose
24	WO70-22, 114.2%	ML	SILT: light yellowish brown, with gravel, rounded to sub-angular, some sand, trace clay, trace cobbles, max. size 8.5cm, moist, soft to firm
		CL	SILTY CLAY: light yellowish brown, with gravel, rounded to angular, max. size 5.5cm, with sand, TILL, moist, stiff
25		GM	GRAVELLY SILT: olive brown, angular, some sand, some cobbles, max. size 9.0cm, dry, soft to firm
		GP	GRAVELLY SAND: coarse, brown to strong brown, some silt, rounded, max. size 4.0cm, moist, soft
	WO70-23	GW	

WO70 (Monitoring Well)

Depth (m)	Core No. and % Recovery	USCS	Lithological Description
	WO70-23, 150.9%	GW	SILTY SANDY GRAVEL: light yellowish brown, some clay, trace cobbles, rounded to sub-angular, max. size 8.0cm, moist, soft
		SC	SANDY CLAY: coarse, pale brown, some gravel, trace cobbles, rounded, max. size 9.0cm, some silt further downcore, moist
26	WO70-24, 113.7%	GP	GRAVEL: light brownish grey, some coarse sand, trace silt, rounded to sub-angular, max. size 6.0cm, moist, loose
		GP	GRAVEL: light brownish grey, with coarse sand, trace cobbles, max. size 9.5cm, rounded to sub-angular, moist, loose to soft
		GC	CLAYEY GRAVEL: light brownish grey, some coarse sand, trace cobbles, max. size 8.5cm, rounded to sub-rounded, moist to wet, loose to soft
27	WO70-25, 86.9%	SP	SAND: medium, brown, moist, poorly graded, soft
		SP	SAND: coarse, brown to strong brown, some gravel, sub-angular to round, max. size 6.0cm, moist, loose, high energy marine
	WO70-26, 94.5%	SP	SAND: coarse, brown to strong brown, with gravel, sub-angular to round, max. size 4.5cm, moist to wet, loose
		GP	GRAVEL: greyish brown, mostly 1.5 - 3.0cm diameter, rounded, trace sand, trace cobbles, max. size 9.0cm, moist to wet, loose
28		SW-SP	SAND: coarse, greyish brown, some silt, some gravel, rounded to sub-rounded, trace cobbles, max. size 7.5cm, moist to wet, loose
		SM	SILTY SAND: coarse, pale brown, trace gravel, rounded, max. size 3.0cm, some clay, increasing clay content downcore, moist to wet, loose
29	WO70-27, 105.0%	SM	SILTY SAND: coarse, pale brown, trace gravel, rounded, max. size 2.0cm, wet, loose
	WO70-28, 84.0%	GW	GRAVEL: pale brown, with silt, some coarse sand, rounded to sub-rounded, max. size 4.5cm, moist to wet, loose
30		SW	SILTY GRAVELLY SAND: coarse, pale brown, rounded to sub-angular, some clay, some cobbles, max. size 10.0cm, finer gravel downcore, less clay and silt downcore, wet, soft
		GW	SANDY GRAVEL: pale brown, coarse sand, with silt, rounded, with silt, trace cobbles, max. size 10.0cm, wet, loose
31		GW	SANDY GRAVEL: pale brown, with silt, coarse sand, rounded to sub-rounded, trace cobbles, max. size 8.5cm, wet, loose

WO70 (Monitoring Well)

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
				GW	
		WO70-29, 89.4%		GW	CLAYEY SANDY GRAVEL: light olive brown, some silt, coarse sand, rounded to sub-angular, trace cobbles, max. size 8.5cm, wet, soft
				GP	GRAVEL: light greyish brown, some sand, trace silt, sub-angular to sub-rounded, some cobbles, max. size 8.5cm, wet, loose
32				GW	SILTY SANDY GRAVEL: light olive brown, rounded to sub-rounded, coarse sand, trace cobbles, max. size 7.5cm, moist, soft
		WO70-30, 113.2%		ML	SILT: grey to light brownish grey, some coarse sand, some gravel, sub-rounded to sub-angular, max. size 3.5cm, moist, stiff
33					
		WO70-31, 112.4%		ML	SILT: grey to light brownish grey, some coarse sand, some gravel, rounded to sub-angular, mostly rounded gravel, max. size 5.5cm, dry, stiff to hard
34					
35					

Notes:
- for 5' cores, percent recovery based on a total core length of 1.524m
- developed January 19, 2007 with a Monsoon pump
- pumped water until clear; total water pumped 225L
- on Dodge Line near the 401
- water level measured from top of PVC pipe

WO71-D (Monitoring Well)

Date Drilled: December 6, 2006
Drilling Inspector: Joanna Passmore
Drillers: Boart Longyear - SDS Drilling
Method: Rotosonic Mini Sonic Drill Rig 4x6" system
Total Depth of Boring: 22.86m
Depth to water: 2.50mbgs (NAD83) (Measured January 27, 2007)
Ground Elevation: 312.90masl (NAD83)
Top of PVC riser elevation: 312.79m (NAD83)
Location: UTM17 North 4770550.17m, East 519049.97m
Originally Surveyed: March 28, 2007
Survey Corrected: June 22, 2007
Installation: - 2.00" Schedule 40 PVC riser and screen
- holeplug from 13.56mbgs to 16.61mbgs
- screen from 16.76mbgs to 20.42mbgs
- sand pack from 16.61mbgs to 19.81mbgs
- grout from 0mbgs to 13.56mbgs
Logged By: Geoff Moroz, Jaqueline Kreller
Last Updated: June 25, 2007

USCS = Unified Soil Classification System

mbgs = Metres Below Ground Surface

masl = Metres Above Sea Level

Well Construction Legend:

- Well Screen
- Water Level
- Hole Plug
- Bentonite Grout
- Sand pack

Depth (m)	Core No. and % Recovery	USCS	Lithological Description
0	WO71-1, 68.9% of 1.524m	Pt	TOPSOIL: dark brown, with sand, medium sandy topsoil, with gravel, moist
		Pt	TOPSOIL: dark brown, with silt, some clay, moist
1			SANDY CLAY: dark greyish brown with mottle reddish brown patches, with organics, with silt, some rounded gravel, max. size 3.0cm, coarse sand, wet, loose
		SC	
2	WO71-2, 69.6% of 1.524m	CL	CLAY: light brown to brown, some gravel, trace coarse sand, trace cobbles, max. size 9.0cm,
3	WO71-3, 84.6% of 1.524m	CL	CLAY: light brown to brown, with gravel, angular to rounded, max. size 5.5cm, appears to be fatty clay, cobbles become more rounded downcore, trace sand, moist, soft
4			
5	WO71-4, 100.4% of 1.524m	CL	CLAY: light brown to brown, with gravel, sub-angular to round, trace cobbles, max. size 10.0cm, some sand, some silt, moist to wetter at either end of core
			CLAYEY SILT: light brown to brown, some medium to coarse sand, trace gravel, trace cobbles, max. size 8.0cm, very wet (soupy), loose
6		CL	

WO71-D (Monitoring Well)

Core No. and % Recovery	USCS	Lithological Description
WO71-5, 82.7% of 1.524m	CL	SILTY CLAY: light yellowish brown, with coarse sand, trace gravel, max. size 2cm, poorly graded, moist
	CL	CLAY: greyish brown, some silt, trace fine sand, trace gravel, max. size 2cm, more clayey at 108cm and on downcore, moist
WO71-6, 98.4% of 1.524m	SM	SANDY SILT: dark grey, fine to coarse sand, trace gravel, sub-angular, max. size 2.5cm, mosit, soft
	SM	SILTY SAND: fine, light yellowish brown, trace gravel, angular to rounded, trace cobbles, max. size 9.0cm, moistly rounded, trace clay, moist, soft
	SM	SANDY SILT: light yellowish brown, with gravel, moistly rounded to sub-angular, fine sand, trace cobbles, max. size 10.5cm, moist, loose
WO71-7, 92.6% of 1.22m	SM	SILTY SAND: fine, brown, some gravel, sub-rounded, max. size 2cm, moist
WO71-8, 91.8% of 1.83m	SM	SILTY SAND: fine, greyish brown, some gravel, some cobbles, max. size 12cm, rounded, wet
	SP	SAND: medium, strong brown, moist
	ML	SILT: greyish brown, hard, trace clay, trace gravel, max. size 1.5cm, dry
	CL	CLAY: greyish brown, some gravel, sub-rounded, moist
WO71-9, 116.8% of 1.524m	ML	SILT: grey, with fine sand, trace clay, firm, gets sandier downcore from 59-118cm, gets more clayey and gravelly from 118-178cm, max. size 2.0cm, dry to moist
WO71-10, 93.3% of 0.943m	ML	CLAYEY SILT: greyish brown, some gravel, dry to moist, hard
WO71-11, 109.5% of 0.63m	ML	SILT: greyish brown, with gravel, rounded to angular (more angular), max. size 6.0cm, moist (moistening downcore), hard
	SP	SAND: medium to coarse, brown, with silt, some gravel, rounded, max. size 4.0cm, moist to wet, soft
WO71-extra slough	SP	
		SAND: coarse to medium, brown, some silt, moist

WO71-D (Monitoring Well)

Core No. and % Recovery	USCS	Lithological Description
WO71-12, 71.5% of 1.524m	SP	SAND: coarse, strong brown, trace silt, moist, extra slough
	GP	SANDY GRAVEL: strong brown, coarse sand, trace silt, max. size 1.0cm, moist
WO71-13, 87.9% of 1.524m	SP	GRAVELLY SAND: coarse, pale brown to brown, some silt, rounded gravel, max. size 2.0cm, moist to wet, loose
	GP	GRAVEL: pale brown, with silt, with sand, rounded, max. size 4.0cm, wet to moist, loose
WO71-14, 69.8% of 1.26m	GP	SANDY GRAVEL: coarse sand, max. size 3.0cm, some silt
	GP	SANDY GRAVEL: light brown, with silt, with clay, mosit to wet
MISSING	-	MISSING
WO71-15, 124.1% of 0.943m	SP	SAND: coarse, greyish brown, with silt, some gravel
	SP	SAND: coarse, greyish brown, some silt, 10cm clay lenses, some gravel, max. size 5.0cm, moist
WO71-16, 89.2% of 1.524m	CL	CLAY: grey, fatty clay, dry to moist
	CL	CLAY: dark greyish brown, trace sand, trace gravel and cobbles, max. size 8cm, sub-angular to sub-rounded, fatty clay, moist

Depth (m): 16, 17, 18, 19, 20, 21, 22

Notes:
- for 5' cores, percent recovery based on a total core length of 1.524m
- developed January 31, 2007 with a Monsoon pump
- pumped water until clear; total water pumped 225L
- Near WO24 at north end of Old Stage Road
- water level measured from top of PVC
- there was extra slough recovered at 15.24m; may represent remaining percentage of WO71-12

WO71-S (Monitoring Well)

University of Waterloo

Date Drilled: December 6, 2006
Drilling Inspector: Joanna Passmore
Drillers: Boart Longyear - SDS Drilling
Method: Rotosonic Mini Sonic Drill Rig 4x6" system
Total Depth of Boring: 10.67m
Depth to water: 2.02mbgs (NAD83) (Measured March 28, 2007)
Ground Elevation: 312.90masl (NAD83)
Top of PVC riser elevation: 312.78m (NAD83)
Location: UTM17 North 4770551.41m, East 519048.83m
Originally Surveyed: March 28, 2007
Survey Corrected: June 22, 2007
Installation: - 2.00" Schedule 40 PVC riser and screen
- holeplug from 6.10mbgs to 8.38mbgs
- screen from 9.14mbgs to 10.36mbgs
- sand pack from 8.38mbgs to 10.06mbgs
- grout from 0mbgs to 6.10mbgs
Logged By: Geoff Moroz, Jaqueline Kreller
Last Updated: June 25, 2007

USCS = Unified Soil Classification System

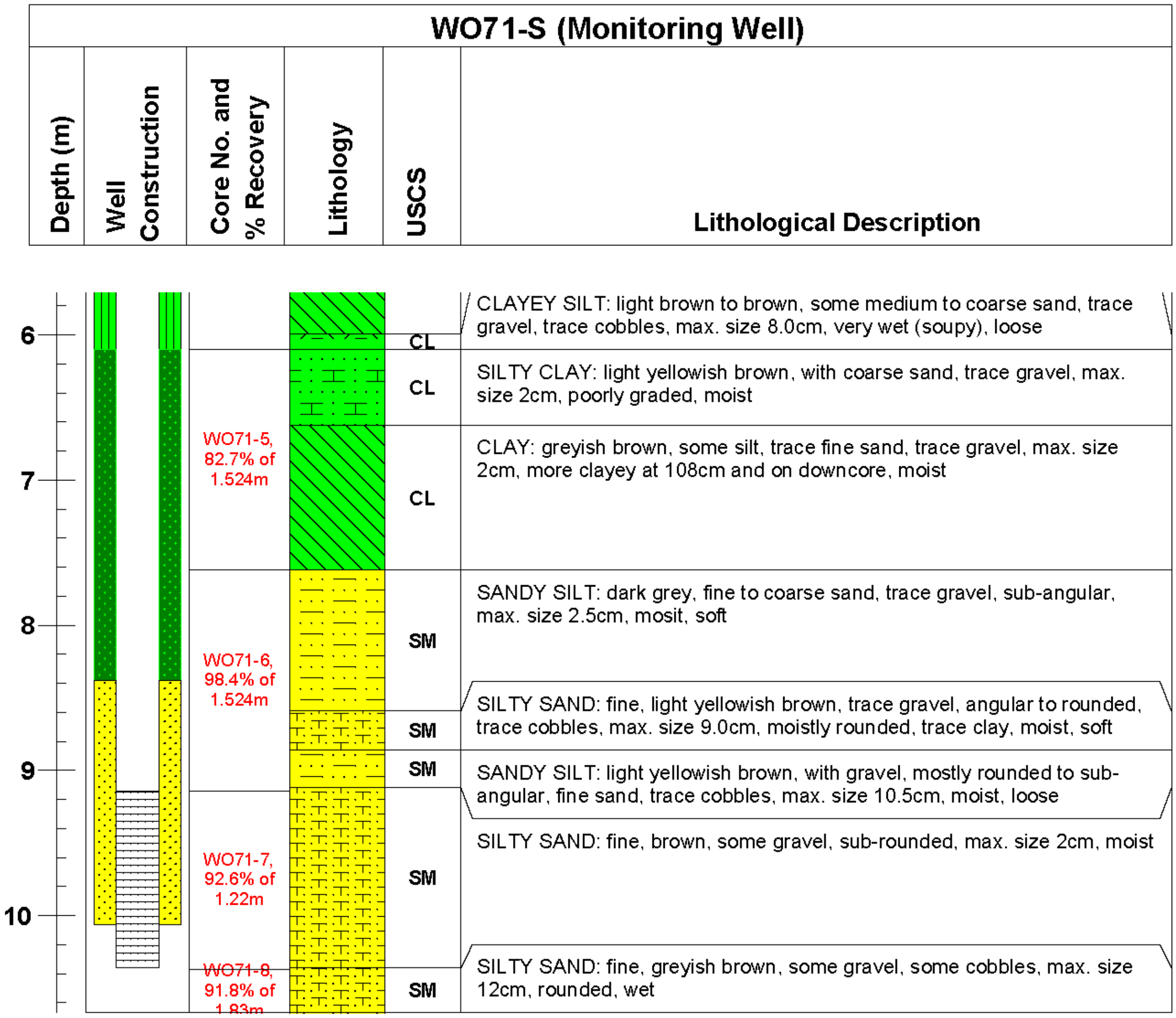
mbgs = Metres Below Ground Surface

masl = Metres Above Sea Level

Well Construction Legend:

- Well Screen
- Water Level
- Hole Plug
- Bentonite Grout
- Sand pack

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
0		WO71-1, 68.9% of 1.524m		Pt	TOPSOIL: dark brown, with sand, medium sandy topsoil, with gravel, moist
1				Pt	TOPSOIL: dark brown, with silt, some clay, moist
				SC	SANDY CLAY: dark greyish brown with mottle reddish brown patches, with organics, with silt, some rounded gravel, max. size 3.0cm, coarse sand, wet, loose
2		WO71-2, 69.6% of 1.524m		CL	CLAY: light brown to brown, some gravel, trace coarse sand, trace cobbles, max. size 9.0cm,
3		WO71-3, 84.6% of 1.524m		CL	CLAY: light brown to brown, with gravel, angular to rounded, max. size 5.5cm, appears to be fatty clay, cobbles become more rounded downcore, trace sand, moist, soft
4					
5		WO71-4, 100.4% of 1.524m		CL	CLAY: light brown to brown, with gravel, sub-angular to round, trace cobbles, max. size 10.0cm, some sand, some silt, moist to wetter at either end of core


WO71-S (Monitoring Well)
Depth (m)
Well Construction
Core No. and % Recovery
Lithology
USCS
Lithological Description
6
7
8
9
10
CL
CLAYEY SILT: light brown to brown, some medium to coarse sand, trace gravel, trace cobbles, max. size 8.0cm, very wet (soupy), loose
CL
SILTY CLAY: light yellowish brown, with coarse sand, trace gravel, max. size 2cm, poorly graded, moist
WO71-5, 82.7% of 1.524m
CL
CLAY: greyish brown, some silt, trace fine sand, trace gravel, max. size 2cm, more clayey at 108cm and on downcore, moist
WO71-6, 98.4% of 1.524m
SM
SANDY SILT: dark grey, fine to coarse sand, trace gravel, sub-angular, max. size 2.5cm, mosit, soft
SM
SILTY SAND: fine, light yellowish brown, trace gravel, angular to rounded, trace cobbles, max. size 9.0cm, moistly rounded, trace clay, moist, soft
SM
SANDY SILT: light yellowish brown, with gravel, mostly rounded to sub-angular, fine sand, trace cobbles, max. size 10.5cm, moist, loose
WO71-7, 92.6% of 1.22m
SM
SILTY SAND: fine, brown, some gravel, sub-rounded, max. size 2cm, moist
WO71-8, 91.8% of 1.83m
SM
SILTY SAND: fine, greyish brown, some gravel, some cobbles, max. size 12cm, rounded, wet

WO72-D (Monitoring Well)

University of Waterloo

Date Drilled: December 15 - 18, 2006
Drilling Inspector: Jamie Koch
Drillers: Boart Longyear - SDS Drilling
Method: Rotosonic Mini Sonic Drill Rig 4x6" system
Total Depth of Boring: 28.96m
Depth to water: 10.98mbgs (NAD83) (Measured April 4, 2007)
Ground Elevation: 309.06masl (NAD83)
Top of PVC riser elevation: 310.01m (NAD83)
Location: UTM17 North 4770579.85m, East 519790.61m
Originally Surveyed: March 28, 2007
Survey Corrected: June 22, 2007
Installation: - 2.00" Schedule 40 PVC riser and screen
- screen from 17.87mbgs to 20.67mbgs
- sand pack from 16.61mbgs to 21.34mbgs
- bentonite plug from 13.41mbgs - 16.61mbgs & from 21.34mbgs - 28.96mbgs
- bentonite from 0.76mbgs to 13.41mbgs
Logged By: Geoff Moroz, Jaqueline Kreller
Last Updated: June 25, 2007

USCS = Unified Soil Classification System

mbgs = Metres Below Ground Surface

masl = Metres Above Sea Level

Well Construction Legend:

Well Screen — Water Level

Bentonite Plug

Bentonite

Sand pack

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
0				-	MISSING: probably pushed to the side
1		WO72-1		ML	SILT: dark yellowish brown, with gravel, moist, soft
2				CL	CLAYEY SILT: dark yellowish brown, with gravel, with medium sand, moist, soft to firm
				SC-SW	CLAYEY GRAVELLY SAND: medium to coarse, yellowish brown, some silt, moist, soft
3				GC-GW	CLAYEY SANDY GRAVEL: light yellowish brown, fine sand, angular to round, max. size 6.5cm, moist, soft
4				GC-SC	GRAVELLY SANDY CLAY: light yellowish brown, angular to rounded, max. size 5.0cm, medium to coarse sand, trace silt, wet, soft
		WO72-2a/b		GW	SANDY GRAVEL: light olive brown, fine sand, rounded to sub-rounded, max. size 6.5cm, mostly large gravel, with silt, wet, loose
5				CL-GC	SILTY GRAVELLY CLAY: light olive brown, some fine sand, angular to sub-rounded, trace cobbles, max. size 8.0cm, less silty downcore, moist to soupy downcore, soft to loose downcore

WO72-D (Monitoring Well)

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
				-	MISSING: possibly pushed aside or compressed
6		WO72-3		CL	CLAYEY SILT: light olive brown, some fine sand, some gravel, trace cobbles, max. size 12.5cm, moist, firm
7		WO72-4		CL	CLAYEY SILT: light olive brown, some fine sand, some gravel, trace cobbles, max. size 12.5cm, moist, firm
8		WO72-5		CL	SILTY CLAY: light yellowish brown, some gravel, sub-rounded to angular, trace cobbles, max. size 10.0cm, some fine sand, soft to firm, moist to wet
9		WO72-6		CL	SILTY CLAY: light brownish grey, trace gravel, max. size 2.0cm, angular, dry to moist, hard to stiff
10		WO72-7		CL	SILTY CLAY: light brownish grey, some gravel, max. size 4.0cm, trace fine sand, dry to moist, hard
11		WO72-8		CL	SILTY CLAY: light brownish grey, trace coarse sand, trace gravel, trace cobbles, sub-rounded to sub-angular, max. size 10.0cm, moist to dry downcore, firm to hard downcore, less clay downcore
12				CL	CLAY: light greyish brown, some silt, trace coarse sand, trace rounded gravel, max. size 1.0cm, moist, soft
				SC	SANDY CLAY: very pale brown, some silt, some gravel, rounded to angular, max. size 3.0cm, coarse sand, moist to dry, soft
				SP	SAND: fine, light olive brown, some silt, some clay, wet (soupy), soft
13		WO72-9		SC-GC	SANDY GRAVELLY CLAY: light olive brown, medium to coarse sand, angular gravel, max. size 5.0cm, mottled red, white and brown at 13.04m, less gravelly after 13.04m
		WO72-10		SP	SAND: coarse, olive brown, moist, loose

WO72-D (Monitoring Well)

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
14		WO72-11		SP	GRAVELLY SAND: coarse, pale yellow, trace silt, rounded gravel, max. size 1.5cm, moist, loose
				SP	SAND: coarse, light yellowish brown, trace silt, trace rounded gravel, trace cobble, max. size 11.0cm, moist, loose
15				GP	SANDY GRAVEL: pale yellow, rounded to sub-anglar, max. size 5.0cm, trace silt, wet, loose
16		WO72-12		GP	SANDY GRAVEL: light olive brown, coarse sand, rounded to sub-angular, some silt, trace cobbles, max. size 9.5cm, grading to coarse sand with gravel by 15.66m, moist, soft
17		WO72-13		GP	SANDY GRAVEL: light yellowish brown, rounded, coarse sand, max. size 6.5cm, trace silt, moist, loose
		WO72-14		SP	SAND: coarse, light olive brown, some rounded gravel, max. size 6.5cm, increased to gravel from 17.66m on, trace silt, moist, loose
18				GP	SANDY GRAVEL: light olive brown, coarse sand, trace silt, rounded gravel, max. size 6.5cm, moist to wetter downcore
19		WO72-15		GP	SANDY GRAVEL: light yellowish brown, coarse sand, rounded gravel, max. size 6.0cm, mostly less than 1.0cm, trace silt, cobble at the end of the section, max. size 9.0cm
20		WO72-16		GP	SANDY GRAVEL: light olive brown, coarse sand, large gravel (5.0cm+), trace cobbles, max. size 7.5cm, rounded to sub-angular, trace silt, moist, loose
		WO72-17		SP	SAND: medium, dark olive to olive brown, a couple of chunks of pure clay within the sand, moist to wet, loose
21				SM	SANDY GRAVELLY SILT: light yellowish brown, with clay, angular to sub-angular, max. size 6.0cm, wet (soupy), soft, orange colour from 20.53 - 20.57m
				SW	SAND: medium, grey, with silt, some clay, trace cobbles separating the next layer, max. size 9.0cm, angular, very gravelly and angular from 21.03 - 21.22m, wet, soft
22		WO72-18		CL	CLAYEY SILT: grey, trace medium sand, clay content decreasing downcore, wet to moist downcore, soft

WO72-D (Monitoring Well)

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
					CLAYEY SILT: grey, some fine sand, some angular gravel, max. size 4.0cm, moist, firm to soft, increasing clay content between 21.82 - 22.10m, broken up between 22.18 - 22.54m
23		WO72-19		CL	CLAY: grey, trace medium sand, angular gravel, max. size 6.0cm, moist to wet, soft
				ML	SILT: grey, some angular to rounded gravel, dry, stiff to hard, some broken up chunks
24		WO72-20		ML	SILT: grey, some round to angular gravel, max. size 5.0cm, trace coarse sand, trace clay, moist to wet, soft
25		WO72-21		CL	CLAY: grey, some silt, some gravel, trace fine sand, moist to dry, soft to firm
26 27		WO72-22		CL	CLAYEY SILT: grey, some fine sand, trace gravel, rounded to angular, max. size 4.0cm, moist, stiff, broken up from 26.90 - 27.31m
28		WO72-23		CL	CLAY: grey, trace rounded to angular gravel, max. size 5.0cm, trace medium to coarse sand, moist, soft to firm

Notes:
- for 5' cores, percent recovery based on a total core length of 1.524m
- developed January 17, 2007 with a Monsoon pump
- total water pumped: 405L

WO72-S (Monitoring Well)

Date Drilled: December 7 - 14, 2006
Drilling Inspector: Jamie Koch
Drillers: Boart Longyear - SDS Drilling
Method: Rotosonic Mini Sonic Drill Rig 4x6" system
Total Depth of Boring: 16.46m
Depth to water: 11.03mbgs (NAD83) (Measured April 4, 2007)
Ground Elevation: 309.09masl (NAD83)
Top of PVC riser elevation: 310.04m (NAD83)
Location: UTM17 North 4770580.01m, East 519792.67m
Originally Surveyed: March 28, 2007
Survey Corrected: June 22, 2007
Installation: - 2.00" Schedule 40 PVC riser and screen
- screen from 13.41mbgs to 16.40mbgs
- sand pack from 12.34mbgs to 16.46mbgs
- grout from 1.52mbgs to 10.06mbgs
- bentonite plug from 0mbgs - 1.52mbgs & 10.06mbgs - 12.34mbgs
Logged By: Geoff Moroz, Jaqueline Kreller
Last Updated: June 25, 2007

University of Waterloo

USCS = Unified Soil Classification System
mbgs = Metres Below Ground Surface
masl = Metres Above Sea Level

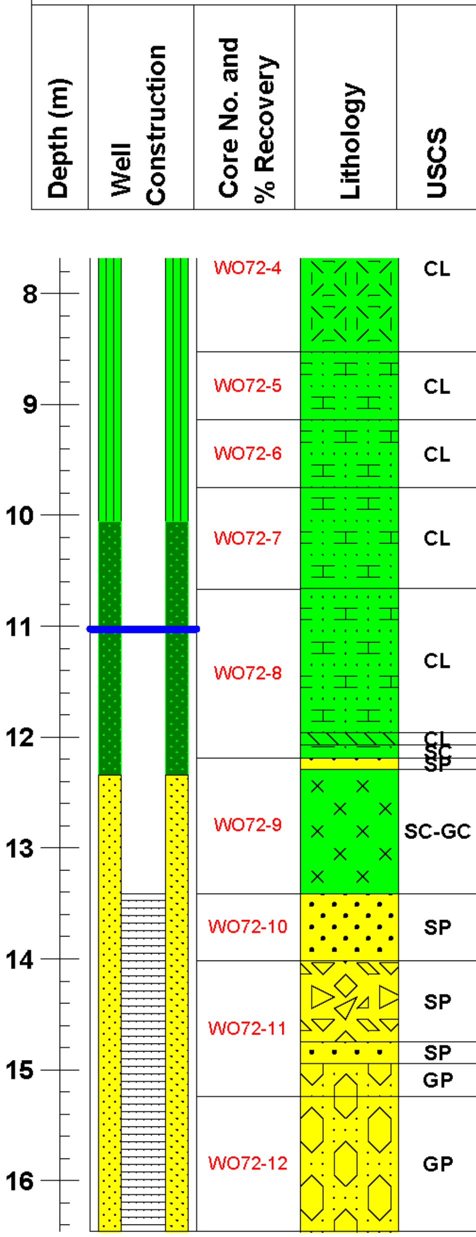
Well Construction Legend:

- Well Screen
- Water Level
- Bentonite Plug
- Bentonite Grout
- Sand pack

Depth (m): 0, 1, 2, 3, 4, 5, 6, 7

Core No. and % Recovery	USCS	Lithological Description
WO72-1	-	MISSING: probably pushed to the side
WO72-1	ML	SILT: dark yellowish brown, with gravel, moist, soft
WO72-1	CL	CLAYEY SILT: dark yellowish brown, with gravel, with medium sand, moist, soft to firm
WO72-1	SC-SW	CLAYEY GRAVELLY SAND: medium to coarse, yellowish brown, some silt, moist, soft
WO72-2a/b	GC-GW	CLAYEY SANDY GRAVEL: light yellowish brown, fine sand, angular to round, max. size 6.5cm, moist, soft
WO72-2a/b	GC-SC	GRAVELLY SANDY CLAY: light yellowish brown, trace silt, angular to rounded, max. size 5.0cm, medium to coarse sand, wet, soft
WO72-2a/b	GW	SANDY GRAVEL: light olive brown, fine sand, rounded to sub-rounded, max. size 6.5cm, mostly large gravel, with silt, wet, loose
WO72-2a/b	CL-GC	SILTY GRAVELLY CLAY: light olive brown, some fine sand, angular to sub-rounded, trace cobbles, max. size 8.0cm, less silty downcore, moist to soupy downcore, soft to loose downcore
WO72-2a/b	-	MISSING: possibly pushed aside or compressed
WO72-3	CL	CLAYEY SILT: light olive brown, some fine sand, some gravel, trace cobbles, max. size 12.5cm, moist, firm
		CLAYEY SILT: light olive brown, some fine sand, some gravel, trace cobbles, max. size 12.5cm, moist, firm

WO72-S (Monitoring Well)



Lithological Description

SILTY CLAY: light yellowish brown, some gravel, sub-rounded to angular, trace cobbles, max. size 10.0cm, some fine sand, soft to firm, moist to wet

SILTY CLAY: light brownish grey, trace gravel, max. size 2.0cm, angular, dry to moist, hard to stiff

SILTY CLAY: light brownish grey, some gravel, max. size 4.0cm, trace fine sand, dry to moist, hard

SILTY CLAY: light brownish grey, trace coarse sand, trace gravel, trace cobbles, max. size 10.0cm, sub-rounded to sub-angular, moist to dry downcore, firm to hard downcore, less clay downcore

CLAY: light greyish brown, some silt, trace coarse sand, trace rounded gravel, max. size 1.0cm, moist, soft

SANDY CLAY: very pale brown, some silt, some gravel, rounded to angular, coarse sand, max. size 3.0cm, moist to dry, soft

SAND: fine, light olive brown, some silt, some clay, wet (soupy), soft

SANDY GRAVELLY CLAY: light olive brown, medium to coarse sand, angular gravel, max. size 5.0cm, mottled red, white and brown at 13.04m, less gravelly after 13.04m

SAND: coarse, olive brown, moist, loose

GRAVELLY SAND: coarse, pale yellow, trace silt, rounded gravel, max. size 1.5cm, moist, loose

SAND: coarse, light yellowish brown, trace silt, trace rounded gravel, trace cobble, max. size 11.0cm, moist, loose

SANDY GRAVEL: pale yellow, rounded to sub-anglar, trace silt, max. size 5.0cm, wet, loose

SANDY GRAVEL: light olive brown, coarse sand, rounded to sub-angular, some silt, trace cobbles, max. size 9.5cm, grading to coarse sand with gravel by 15.66m, moist, soft

Notes:
- for 5' cores, percent recovery based on a total core length of 1.524m
- well is in the road box on the right side of Curry road heading south; the first wells on Curry
- developed January 17 with a Monsoon pump
- total water pumped: 90L

WO73-D (Monitoring Well)

University of Waterloo

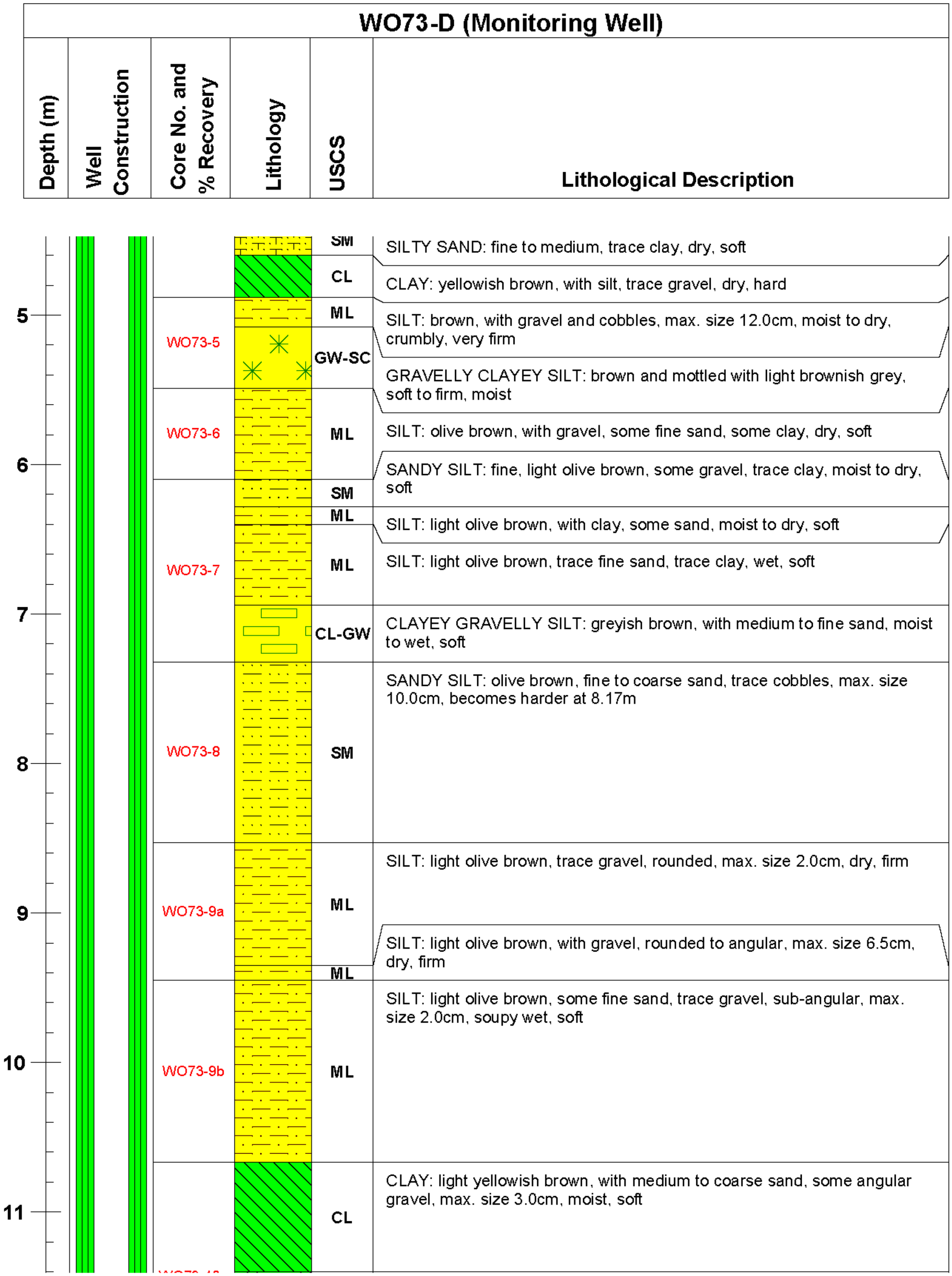
Date Drilled: December 15 - 18, 2006
Drilling Inspector: Jamie Koch
Drillers: Boart Longyear - SDS Drilling
Method: Rotosonic Mini Sonic Drill Rig 4x6" system
Total Depth of Boring: 38.10m
Depth to water: 18.33mbgs (NAD83) (Measured April 9, 2007)
Ground Elevation: missed ground shot when surveying (NAD83)
Top of PVC riser elevation: 317.30m (NAD83)
Location: UTM17 North 4770754.01m, East 519937.07m
Originally Surveyed: March 28, 2007
Survey Corrected: June 22, 2007
Installation: - 2.00" Schedule 40 PVC riser and screen
- screen from 22.10mbgs to 25.86mbgs
- sand pack from 21.95mbgs to 26.25mbgs
- grout from 0mbgs to 19.81mbgs
- bentonite plug from 19.81mbgs to 21.95mbgs
Logged By: Geoff Moroz, Jaqueline Kreller
Last Updated: June 25, 2007

USCS = Unified Soil Classification System
mbgs = Metres Below Ground Surface
masl = Metres Above Sea Level

Well Construction Legend:

- Well Screen
- Water Level
- Bentonite Plug
- Bentonite Grout
- Sand pack

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
0		WO73-1		SM	SANDY SILT: dark yellowish brown, some clay, trace gravel, moist, soft
1				CL	SILTY CLAY: dark yellowish brown, with fine to medium sand, some gravel, moist, soft
		WO73-2		ML	SILT: dark yellowish brown, with clay, some gravel, rounded to angular, max. size 5.0cm, trace coarse sand, moist, soft
2				CL	CLAYEY SILT: brown, trace coarse sand, grading to clay with some silt downcore, trace gravel, angular to sub-rounded, max. size 4.5cm, yellowish brown sand lenses at 3.23-2.34m, black sand lenses at 2.77cm, moist, soft
3				CL	SILTY CLAY: dark yellowish brown, with medium to coarse sand, some gravel, some organics (grass, roots), moist, soft
		WO73-3		CL	SILTY CLAY: dark yellowish brown, some gravel, dry to moist, firm
		WO73-4		CL	CLAY: marbled dark and light yellowish brown, with silt, trace gravel, dry, hard
4				SM	SILTY SAND: fine to medium, yellowish brown, moist to dry, soft
				SM-SC	SILTY CLAYEY SAND: medium to fine, yelloiwsh brown, trace gravel, dry, firm
				SM	



WO73-D (Monitoring Well)
Depth (m)
Well Construction
Core No. and % Recovery
Lithology
USCS
Lithological Description
5
6
7
8
9
10
11
WO73-5
WO73-6
WO73-7
WO73-8
WO73-9a
WO73-9b
SM
CL
ML
GW-SC
ML
SM
ML
ML
CL-GW
SM
ML
ML
ML
CL
SILTY SAND: fine to medium, trace clay, dry, soft
CLAY: yellowish brown, with silt, trace gravel, dry, hard
SILT: brown, with gravel and cobbles, max. size 12.0cm, moist to dry, crumbly, very firm
GRAVELLY CLAYEY SILT: brown and mottled with light brownish grey, soft to firm, moist
SILT: olive brown, with gravel, some fine sand, some clay, dry, soft
SANDY SILT: fine, light olive brown, some gravel, trace clay, moist to dry, soft
SILT: light olive brown, with clay, some sand, moist to dry, soft
SILT: light olive brown, trace fine sand, trace clay, wet, soft
CLAYEY GRAVELLY SILT: greyish brown, with medium to fine sand, moist to wet, soft
SANDY SILT: olive brown, fine to coarse sand, trace cobbles, max. size 10.0cm, becomes harder at 8.17m
SILT: light olive brown, trace gravel, rounded, max. size 2.0cm, dry, firm
SILT: light olive brown, with gravel, rounded to angular, max. size 6.5cm, dry, firm
SILT: light olive brown, some fine sand, trace gravel, sub-angular, max. size 2.0cm, soupy wet, soft
CLAY: light yellowish brown, with medium to coarse sand, some angular gravel, max. size 3.0cm, moist, soft

WO73-D (Monitoring Well)

Core No. and % Recovery	USCS	Lithological Description
WO73-10a	GC	GRAVELLY CLAY: light yellowish brown, with medium to coarse sand, angular to rounded, max. size 6.0cm, moist to wet (wetter downcore)
	CL	CLAY: light yellowish brown, with medium to coarse sand, wet
WO73-10b	SC	SANDY CLAY: light yellowish brown, medium to coarse sand, some silt, trace gravel, sub-angular, max. size 2.0cm, moist, soft
	GC	CLAYEY GRAVEL: light yellowish brown, angular, max. size 7.0cm, with coarse sand, wet, soft
	GC	CLAYEY GRAVEL: light brownish grey, with sand, large gravel, rounded to angular, max. size 4.0cm, wet, loose
WO73-11a	SW	SAND: coarse, brown, some clay, some gravel, rounded to sub-rounded, max. size 6.0cm, wet, loose
WO73-11b	CL	CLAY: very pale brown, with coarse sand, with gravel, angular, trace cobbles, max. size 7.5cm, wet, soft
	GC	CLAYEY GRAVEL: very pale brown, angular, max. size 6.5cm, trace coarse sand, wet, soft
	GW	GRAVELLY SAND: medium to coarse, brown, some clay, trace cobbles, max. size 7.0cm, angular, moist to wet, soft
	ML	SILT: light olive yellow, trace rounded to sub-rounded gravel, max. size 5.0cm, dry, soft
WO73-12a	SM-SW	SILTY GRAVELLY SAND: medium to coarse, light olive brown, with clay, wet to moist, soft
	SM	SILTY SAND: medium to coarse, light olive brown, some small gravel, wet, soft
	SM-SW	SILTY GRAVELLY SAND: coarse, light olive brown, wet, soft
	SM	SILTY SAND: coarse to medium, light brownish grey, with clay, with gravel, wet, soft
	SM-SW	SILTY GRAVELLY SAND: coarse, light brownish grey, with cobbles, wet, soft
	SM	SILTY SAND: coarse, light brownish grey, with clay, with gravel, wet, soft
WO73-12b	SC	SANDY CLAY: light yellowish brown, trace gravel, angular, trace cobbles, max. size 9.0cm, grading to gravelly clay by 16.57m, wet and soupy, loose
WO73-12c	SP	SAND: fine to coarse, olive brown, with silt, dry, soft

Depth (m): 12, 13, 14, 15, 16, 17, 18

WO73-D (Monitoring Well)

Core No. and % Recovery	USCS	Lithological Description
WO73-13a	SP	SAND: medium to coarse, olive brown, trace silt, trace rounded gravel, max. size 2.5cm, firm to stiff
WO73-13b	SM	SILTY SAND: medium to coarse, brown, some small gravel, rounded to sub-angular, max. size 4.5cm, moist to wet, soft
	SP	SAND: fine, light olive to olive brown, trace rounded gravel, max. size 3.0cm, moist, soft to firm
	SP	SAND: fine, light olive to olive brown, some silt, trace rounded gravel, max. size 3.0cm, moist, soft to firm
WO73-13c	SP	SAND: fine, light olive brown, grades from fine to medium sand downcore, firm, wet (possibly from being exposed to rain outside)
	SC	SANDY CLAY: light olive brown to pale brown, medium sand, trace gravel, max. size 5.5cm, sub-rounded to sub-angular, wet, loose
	GW	SANDY GRAVEL: light olive brown, some clay, trace cobbles, max. size 10.0cm, rounded to angular, wet, stiff
	SM	SANDY SILT: olive yellow, fine sand, some clay, wet, firm
	GW	SILTY GRAVEL: olive yellow, some sand, rounded to angular, some cobbles, max. size 10.5cm, wet, loose
WO73-14a	GC	CLAYEY GRAVEL: pale brown, with medium to coarse sand, mostly angular gravel, some sub-rounded gravel, trace cobbles, max. size 7.0cm, moist, soft to firm
	SW	GRAVELLY SAND: coarse, pale brown, with clay, rounded to angular gravel, max size 6.5cm, decreasing clast size downcore, wet, loose
WO7314-b	GW	SANDY GRAVEL: light yellowish brown, cobbly gravel, well rounded, max. size 7.5cm, coarse sand, with silt, wet, soft to firm
	GW	SANDY GRAVEL: pale yellow, coarse sand, rounded to angular gravel, cobbly, max. size 9.0cm, with clay, wet, soft
WO73-15a	GW	SANDY GRAVEL: light olive brown, rounded to angular, max. size 6.5cm, trace clay, moist, soft
	SC-SW	CLAYEY GRAVELLY SAND: fine to coarse sand, light brownish grey, angular to rounded, some cobbles, max. size 9.0cm, moist, soft

WO73-D (Monitoring Well)

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
		WO73-15b		SC-SW	
26				SC-SW	CLAYEY GRAVELLY SAND: coarse sand, light brownish grey, rounded to sub-angular, max. size 6.5cm, trace silt, wet, loose
				CL	CLAYEY SILT: light brownish grey, some medium sand, some gravel, rounded to sub-angular, max. size 3.5cm, moist, firm
27		WO73-15c		CL	CLAY: grey, grading from some silt to no silt downcore, trace coarse sand, some gravel, rounded to sub-rounded, max. size 3.5cm, moist (wetter downcore), soft to firm (softer downcore)
28		WO73-16a		CL	CLAY: light brownish grey, trace silt, trace medium to coarse sand, some gravel, angular to sub-rounded, trace cobbles, max. size 8.0cm, moist, firm to stiff in middle of core, softer at each end of the core, increasing gravel content downcore
29				CL	CLAYEY SILT: greyish brown, with gravel, moist, crumbly, hard
30		WO73-16b		CL	SILTY CLAY: greyish brown, with gravel, some soft parts, some hard dry parts, moist
		WO73-17		CL	SILTY CLAY: greyish brown, some gravel, dry to moist, firm to hard
31		WO73-18		CL	CLAY: greyish brown, some silt, some angular to sub-rounded gravel, trace cobbles, max. size 12.0cm, trace fine to medium sand, moist, soft
32					SILTY CLAY: greyish brown, with medium to coarse sand, some gravel,

WO73-D (Monitoring Well)

Depth (m): 33, 34, 35, 36, 37, 38

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
				CL	moist, soft
33		WO73-19		CL	CLAY: greyish brown, with silt, some medium to coarse sand, some gravel, moist, soft
34		WO73-20		CL	CLAYEY SILT: greyish brown, some gravel, angular to sub-angular, trace cobbles, max. size 11.0cm, moist, hard
35		WO73-21		CL	CLAY: greyish brown, some silt, trace rounded to angular gravel, max. size 3.0cm, moist, firm
36		WO73-22		CL	CLAY: greyish brown, trace rounded to angular gravel, max. size 4.0cm, trace silt, moist, firm
37–38		WO73-23		CL	CLAY: greyish brown, some rounded to angular gravel, max. size 4.5cm, trace silt, desocated from 36.98 - 37.58m, moist firm (stiffer near end of core), more gravel in desocated section

Notes:
- for 5' cores, percent recovery based on a total core length of 1.524m
- well is in the road box on the right side of Curry road heading south; the first wells on Curry
- developed January 17, 2007 with a Monsoon pump
- total water pumped: 225L

WO74-D (Monitoring Well)

Date Drilled: December 20, 2006
Drilling Inspector: Joanna Passmore
Drillers: Boart Longyear - SDS Drilling
Method: Rotosonic Mini Sonic Drill Rig 4x6" system
Total Depth of Boring: 21.34m
Depth to water: 3.64mbgs (NAD83) (Measured January 10, 2007)
Ground Elevation: 300.75masl (NAD83)
Top of PVC riser elevation: 301.63m (NAD83)
Location: UTM17 North 4770155.97m, East 520056.14m
Originally Surveyed: March 28, 2007
Survey Corrected: June 22, 2007
Installation: - 2.00" Schedule 40 PVC riser and screen
- holeplug from 13.56mbgs to 16.61mbgs
- screen from 14.94mbgs to 17.98mbgs
- sand pack from 16.61mbgs to 20.42mbgs
- grout from 0mbgs to 13.56mbgs
Logged By: Geoff Moroz, Jaqueline Kreller
Last Updated: June 25, 2007

University of Waterloo

USCS = Unified Soil Classification System

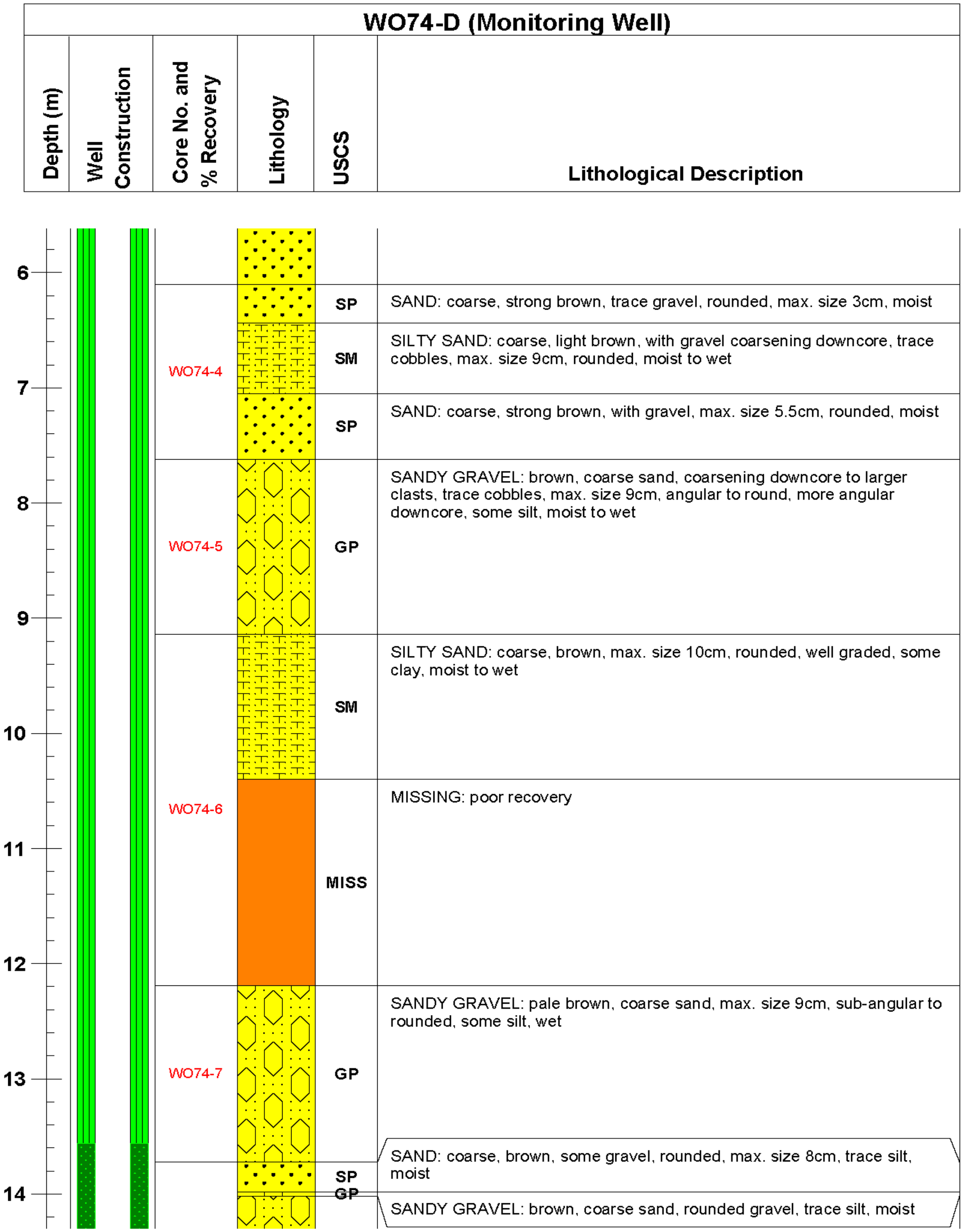
mbgs = Metres Below Ground Surface

masl = Metres Above Sea Level

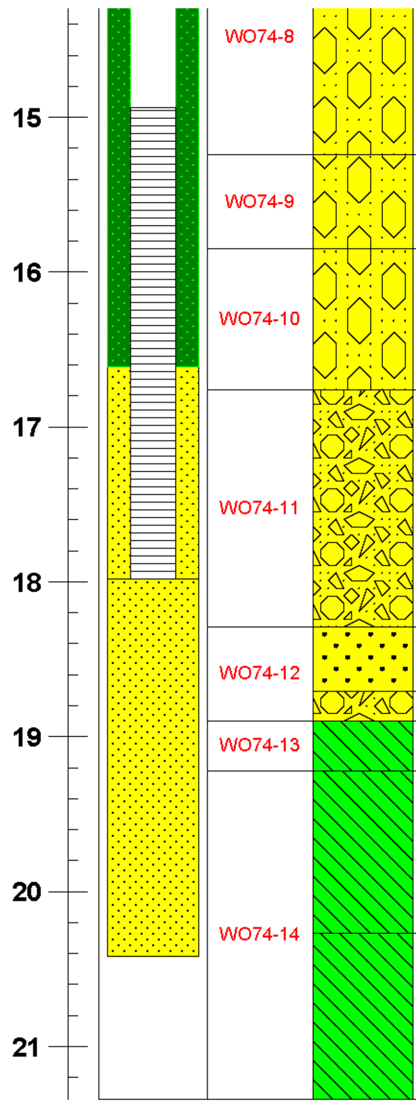
Well Construction Legend:

- Well Screen
- Water Level
- Hole Plug
- Bentonite Grout
- Sand pack

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
0		WO74 1a, 1b		Pt	TOPSOIL: dark brown, moist, organics
				Pt	TOPSOIL: dark brown, thin layer of sand 21 cm downcore, then topsoil again
1				SP	SAND: medium, brown, with silt, trace gravel, max. size 1cm, no gravel beyond 60cm, slightly finer sand also beyoned 60cm, dry
2				MISS	MISSING: poory recovery
3		WO74-2		SC	SILTY CLAY: light brownish grey, with fine to medium sand, moist to wet
				SM	SILTY SAND: fine to medium, light olive brown, wet
				SM	SILTY SAND: fine, light olive brown, wet
4				GM	GRAVELLY SILT: light olive brown, with coarse to medium sand, max. size 5.0cm, trace clay, wet
5		WO74-3		SP	SAND: medium to coarse, dark yellowish brown, some gravel, max. size 6.0cm, some silt, wet


WO74-D (Monitoring Well)
Depth (m)
Well Construction
Core No. and % Recovery
Lithology
USCS
Lithological Description
6
7
8
9
10
11
12
13
14
WO74-4
WO74-5
WO74-6
WO74-7
SP
SAND: coarse, strong brown, trace gravel, rounded, max. size 3cm, moist
SM
SILTY SAND: coarse, light brown, with gravel coarsening downcore, trace cobbles, max. size 9cm, rounded, moist to wet
SP
SAND: coarse, strong brown, with gravel, max. size 5.5cm, rounded, moist
GP
SANDY GRAVEL: brown, coarse sand, coarsening downcore to larger clasts, trace cobbles, max. size 9cm, angular to round, more angular downcore, some silt, moist to wet
SM
SILTY SAND: coarse, brown, max. size 10cm, rounded, well graded, some clay, moist to wet
MISS
MISSING: poor recovery
GP
SANDY GRAVEL: pale brown, coarse sand, max. size 9cm, sub-angular to rounded, some silt, wet
SP
SAND: coarse, brown, some gravel, rounded, max. size 8cm, trace silt, moist
GP
SANDY GRAVEL: brown, coarse sand, rounded gravel, trace silt, moist

WO74-D (Monitoring Well)



Core No. and % Recovery	USCS	Lithological Description
WO74-8	GP	SANDY GRAVEL: coarse sand, round gravel, trace cobbles max. size, 9cm, trace silt, moist
WO74-9	GP	SANDY GRAVEL: coarse sand, angular to rounded, trace cobbles, max. size 9.0cm
WO74-10	GP	SANDY GRAVEL: brown, coarse sand, with cobbles (mostly cobbly, greater than 8cm), max size 9.5cm, with silt, moist
WO74-11	GP	GRAVEL: coarse, light olive brown, rounded gravel, some silt, trace sand, trace cobbles, max. size 8cm, moist to wet
WO74-12	GP	SAND: fine, strong brown, moist, soft
	GW	GRAVEL: brown, with medium sand, some silt, rounded, max. size 6cm, well graded, moist to wet
WO74-13	CL	CLAY: reddish brown, with silt, with gravel, angular, max. size 3cm, moist
WO74-14	CL	CLAY: grey to dark grey, with gravel, rounded, max. size 2.5cm, moist to dry, drying downcore, increased compaction downcore, loose to stiff/hard downcore, moist to dry
	CL	CLAY: grey to greyish brown, with gravel, sub-angular to round, max. size 2.5cm, trace sand, stiff/hard

Notes:
- for 5' cores, percent recovery based on a total core length of 1.524m
- developed January 10, 2007 with a Monsoon pump
- pumped water until clear; total water pumped 90L
- well is down and around driveway into the back left corner of farmers field on left of Curry Rd.
- water level measured from top of PVC pipe, stickup: 0.92m

WO74-M (Monitoring Well)

Date Drilled: December 20, 2006
Drilling Inspector: Joanna Passmore
Drillers: Boart Longyear - SDS Drilling
Method: Rotosonic Mini Sonic Drill Rig 4x6" system
Total Depth of Boring: 14.02m
Depth to water: 3.65mbgs (NAD83) (Measured March 29, 2007)
Ground Elevation: 300.75masl (NAD83)
Top of PVC riser elevation: 301.64m (NAD83)
Location: UTM17 North 4770154.97m, East 520055.03m
Originally Surveyed: March 28, 2007
Survey Corrected: June 22, 2007
Installation: - 2.00" Schedule 40 PVC riser and screen
- holeplug from 9.14mbgs to 11.89mbgs
- screen from 12.50mbgs to 13.72mbgs
- sand pack from 11.89mbgs to 14.02mbgs
- grout from 0mbgs to 9.14mbgs
Logged By: Geoff Moroz, Jaqueline Kreller
Last Updated: June 25, 2007

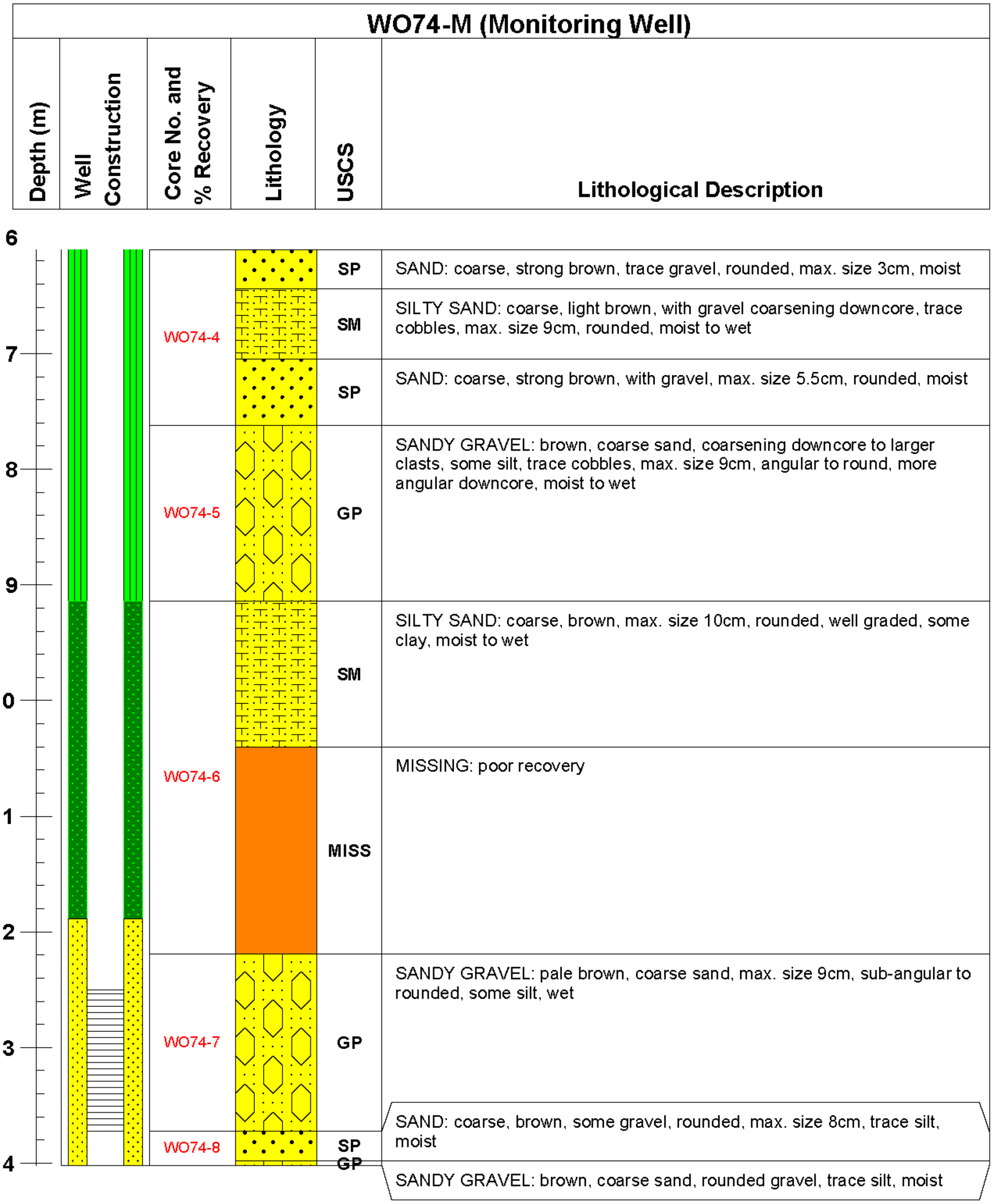
University of Waterloo

USCS = Unified Soil Classification System
mbgs = Metres Below Ground Surface
masl = Metres Above Sea Level

Well Construction Legend:

- Well Screen
- Water Level
- Hole Plug
- Bentonite Grout
- Sand pack

Depth (m)	Core No. and % Recovery	USCS	Lithological Description
0	WO74 1a, 1b	Pt	TOPSOIL: dark brown, moist, organics
		Pt	TOPSOIL: dark brown, thin layer of sand 21 cm downcore, then topsoil again
1		SP	SAND: medium, brown, with silt, trace gravel, max. size 1cm, no gravel beyond 60cm, slightly finer sand also beyoned 60cm, dry
2		MISS	MISSING: poory recovery
3	WO74-2	SC	SILTY CLAY: light brownish grey, with fine to medium sand, moist to wet
		SM	SILTY SAND: fine to medium, light olive brown, wet
		SM	SILTY SAND: fine, light olive brown, wet
4		GM	GRAVELLY SILT: light olive brown, with coarse to medium sand, max. size 5.0cm, trace clay, wet
5	WO74-3	SP	SAND: medium to coarse, dark yellowish brown, some gravel, max. size 6.0cm, some silt, wet
6			



Notes:

- for 5' cores, percent recovery based on a total core length of 1.524m
- developed January 10, 2007 with a Monsoon pump
- pumped water until clear; total water pumped 105L
- well is down and around driveway into the back left corner of farmers field on left of Curry Rd.
- water level measured from top of PVC pipe, stickup: 0.89m

WO74-S (Monitoring Well)

University of Waterloo

Date Drilled: December 20, 2006
Drilling Inspector: Joanna Passmore
Drillers: Boart Longyear - SDS Drilling
Method: Rotosonic Mini Sonic Drill Rig 4x6" system
Total Depth of Boring: 10.67m
Depth to water: 3.66mbgs (NAD83) (Measured March 29, 2007)
Ground Elevation: 300.86masl (NAD83)
Top of PVC riser elevation: 301.72m (NAD83)
Location: UTM17 North 4770154.28m, East 520053.90m
Originally Surveyed: March 28, 2007
Survey Corrected: June 22, 2007
Installation: - 2.00" Schedule 40 PVC riser and screen
- holeplug from 0mbgs to 7.92mbgs
- screen from 9.14mbgs to 10.36mbgs
- sand pack from 7.92mbgs to 10.67mbgs
Logged By: Geoff Moroz, Jaqueline Kreller
Last Updated: June 25, 2007

USCS = Unified Soil Classification System

mbgs = Metres Below Ground Surface

masl = Metres Above Sea Level

Well Construction Legend:

- Well Screen
- Water Level
- Hole Plug
- Bentonite Grout
- Sand pack

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
0		WO74 1a, 1b		Pt	TOPSOIL: dark brown, moist, organics
				Pt	TOPSOIL: dark brown, thin layer of sand 21 cm downcore, then topsoil again
1				SP	SAND: medium, brown, with silt, trace gravel, max. size 1cm, no gravel beyond 60cm, slightly finer sand also beyoned 60cm, dry
2				MISS	MISSING: poory recovery
3		WO74-2		SC	SILTY CLAY: light brownish grey, with fine to medium sand, moist to wet
				SM	SILTY SAND: fine to medium, light olive brown, wet
				SM	SILTY SAND: fine, light olive brown, wet
4				GM	GRAVELLY SILT: light olive brown, with coarse to medium sand, max. size 5.0cm, trace clay, wet
5		WO74-3		SP	SAND: medium to coarse, dark yellowish brown, some gravel, max. size 6.0cm, some silt, wet

WO74-S (Monitoring Well)

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
6					
		WO74-4		SP	SAND: coarse, strong brown, trace gravel, rounded, max. size 3cm, moist
7				SM	SILTY SAND: coarse, light brown, with gravel coarsening downcore, trace cobbles max. size 9cm, rounded, moist to wet
				SP	SAND: coarse, strong brown, with gravel, max. size 5.5cm, rounded, moist
8		WO74-5		GP	SANDY GRAVEL: brown, coarse sand, coarsening downcore to larger clasts, some silt, trace cobbles, max. size 9cm, angular to round, more angular downcore, moist to wet
9		WO74-6		SM	SILTY SAND: coarse, brown, max. size 10cm, rounded, well graded, some clay, moist to wet
10				MISS	MISSING: poor recovery

Notes:

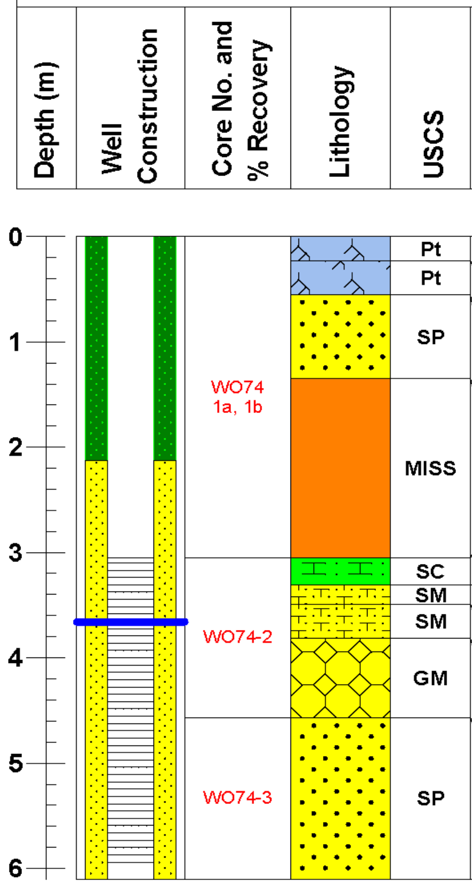
- for 5' cores, percent recovery based on a total core length of 1.524m
- developed January 10, 2007 with a Monsoon pump
- pumped water until clear; total water pumped 135L
- well is down and around driveway into the back left corner of farmers field on left of Curry Rd.
- water level measured from top of PVC pipe, stickup: 0.87m

WO74-WT (Monitoring Well)

Date Drilled: December 20, 2006
Drilling Inspector: Joanna Passmore
Drillers: Boart Longyear - SDS Drilling
Method: Rotosonic Mini Sonic Drill Rig 4x6" system
Total Depth of Boring: 6.10m
Depth to water: 3.66mbgs (NAD83) (Measured March 29, 2007)
Ground Elevation: 300.84masl (NAD83)
Top of PVC riser elevation: 301.64m (NAD83)
Location: UTM17 North 4770152.75m, East 520052.33m
Originally Surveyed: March 28, 2007
Survey Corrected: June 22, 2007
Installation: - 2.00" Schedule 40 PVC riser and screen
- holeplug from 0mbgs to 2.13bgs
- screen from 3.05mbgs to 5.94mbgs
- sand pack from 2.13mbgs to 6.10mbgs
Logged By: Geoff Moroz, Jaqueline Kreller
Last Updated: June 25, 2007

USCS = Unified Soil Classification System
mbgs = Metres Below Ground Surface
masl = Metres Above Sea Level

Well Construction Legend:
Well Screen
Water Level
Hole Plug
Bentonite Grout
Sand pack



USCS	Lithological Description
Pt	TOPSOIL: dark brown, moist, organics
Pt	TOPSOIL: dark brown, thin layer of sand 21 cm downcore, then topsoil again
SP	SAND: medium, brown, with silt, trace gravel, max. size 1cm, no gravel beyond 60cm, slightly finer sand also beyoned 60cm, dry
MISS	MISSING: poory recovery
SC	SILTY CLAY: light brownish grey, with fine to medium sand, moist to wet
SM	SILTY SAND: fine to medium, light olive brown, wet
SM	SILTY SAND: fine, light olive brown, wet
GM	GRAVELLY SILT: light olive brown, with coarse to medium sand, max. size 5.0cm, trace clay, wet
SP	SAND: medium to coarse, dark yellowish brown, some gravel, max. size 6.0cm, some silt, wet

Notes:
- for 5' cores, percent recovery based on a total core length of 1.524m
- developed January 10, 2007 with a Monsoon pump
- pumped water until clear; total water pumped 120L
- well is down and around driveway into the back left corner of farmers field on left of Curry Rd.
- water level measured from top of PVC pipe, stickup: 0.80m

WO75-D (Monitoring Well)

Date Drilled: January 10, 2007
Drilling Inspector: Joanna Passmore
Drillers: Boart Longyear - SDS Drilling
Method: Rotosonic Mini Sonic Drill Rig 4x6" system
Total Depth of Boring: 24.38m
Depth to water: 5.57mbgs (NAD83) (Measured March 29, 2007)
Ground Elevation: 302.80masl (NAD83)
Top of PVC riser elevation: 303.64m (NAD83)
Location: UTM17 North 4770112.04m, East 520013.59m
Originally Surveyed: March 28, 2007
Survey Corrected: June 22, 2007
Installation: - 2.00" Schedule 40 PVC riser and screen
- holeplug from 15.24mbgs to 16.92mbgs & 22.10mbgs to 22.86mbgs
- screen from 18.29mbgs to 21.34mbgs
- sand pack from 16.92mbgs to 22.10mbgs
- grout from 0mbgs to 12.19mbgs
Logged By: Geoff Moroz, Jaqueline Kreller
Last Updated: June 25, 2007

USCS = Unified Soil Classification System

mbgs = Metres Below Ground Surface

masl = Metres Above Sea Level

Well Construction Legend:

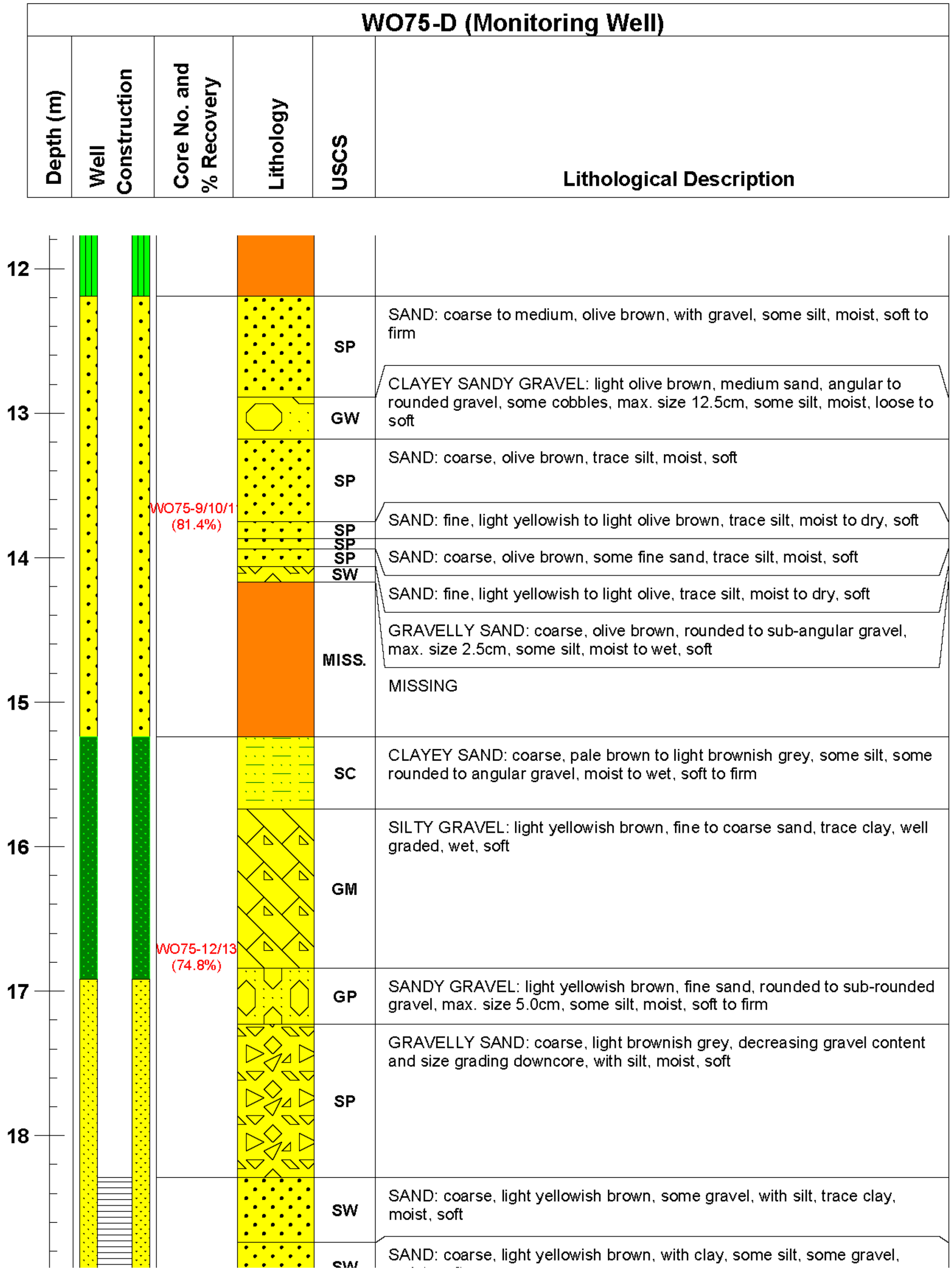
- Well Screen
- Water Level
- Hole Plug
- Bentonite Grout
- Sand pack

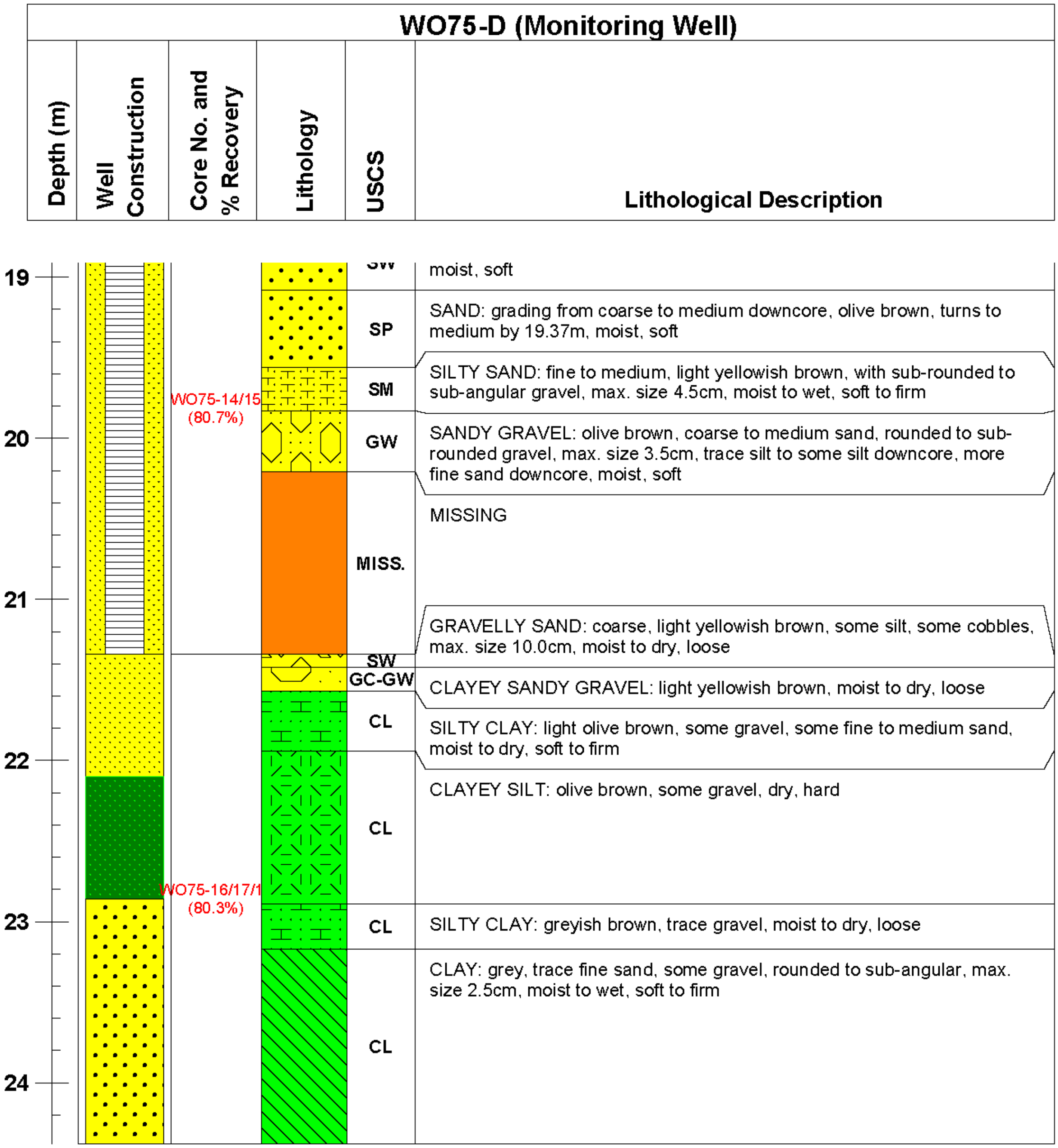
Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
0				Pt	TOPSOIL: dark brown, moist, some gravel
1–2		WO75-1 (52.5%)		SM-GM	SANDY SILT: olive brown, fine to medium sand, with gravel, moist to wet, soft
3				SM	SANDY SILT: light olive brown, medium sand, some clay, some gravel, moist to wet, soft
				SW SW	SAND: coarse, light olive brown, with silt, some gravel, moist, soft
				SM-GM	SAND: medium to coarse sand, light olive brown, with silt, with gravel, some solid lenses of clay, moist, soft
4		WO75-2/3 (62.7%)		SP	SANDY GRAVELLY SILT: light olive brown, rounded to sub-angular gravel, trace cobbles, max. size 7.0cm, mostly fairly large gravel, fine sand, dry, soft

WO75-D (Monitoring Well)

Core No. and % Recovery	USCS	Lithological Description
(62.7%)	SW	SAND: medium, light olive to olive brown, dry, soft
	SW	SAND: medium, light yellowish brown, with clay, some rounded to sub-angular gravel, max. size 2.5cm, dry, soft
WO75-4/5 (62.7%)	SP	SAND: medium, light yellowish brown, some silt, some clay, moist, soft
	SP	SAND: medium to coarse, light yellowish brown, with gravel, some silt, moist, some dry bits, soft
	GW	SANDY SILTY GRAVEL: light olive brown, rounded to sub-rounded, max. size 6.0cm, moist, soft to firm
	SW	GRAVELLY SAND: medium, light yellowish brown, rounded gravel, max. size 6.5cm, moist, loose
	GP	GRAVEL: light greyish brown, rounded to sub-angular gravel, trace coarse sand, trace silt, moist, loose
	SW	GRAVELLY SAND: medium, light olive brown, rounded to sub-angular gravel, max. size 6.5cm, trace silt, moist, loose
	SM	SILTY SAND: medium, light olive brown, with rounded to angular gravel, some clay, decreasing to no clay downcore, moist, soft
	MISS.	MISSING
WO75-6/7/8 (98.1%)	SP	SAND: coarse to medium, light olive brown, with clay, with gravel, moist, soft
	SW	GRAVELLY SAND: coarse to medium, light olive brown, with silt, some cobbles, max. size 10.0cm, trace clay, moist to wet, soft
	SP	SAND: coarse, olive brown, some silt, some rounded gravel, max. size 4.0cm, moist, soft
	GW	SANDY GRAVEL: pale yellow, medium to coarse sand, some clay/silt, round to angular, trace cobbles, max. size 11.0cm, moist, soft to firm
	SC	CLAYEY SAND: medium to fine, light grey to pale yellow, with angular to sub-angular gravel, trace cobbles, max. size 8.0cm, moist to wet, firm
	MISS.	MISSING

Depth (m): 5, 6, 7, 8, 9, 10, 11


WO75-D (Monitoring Well)
Depth (m)
Well Construction
Core No. and % Recovery
Lithology
USCS
Lithological Description
12
13
14
15
16
17
18
WO75-9/10/1
(81.4%)
WO75-12/13
(74.8%)
SP
SAND: coarse to medium, olive brown, with gravel, some silt, moist, soft to firm
GW
CLAYEY SANDY GRAVEL: light olive brown, medium sand, angular to rounded gravel, some cobbles, max. size 12.5cm, some silt, moist, loose to soft
SP
SAND: coarse, olive brown, trace silt, moist, soft
SP
SAND: fine, light yellowish to light olive brown, trace silt, moist to dry, soft
SP
SAND: coarse, olive brown, some fine sand, trace silt, moist, soft
SP
SAND: fine, light yellowish to light olive, trace silt, moist to dry, soft
SW
GRAVELLY SAND: coarse, olive brown, rounded to sub-angular gravel, max. size 2.5cm, some silt, moist to wet, soft
MISS.
MISSING
SC
CLAYEY SAND: coarse, pale brown to light brownish grey, some silt, some rounded to angular gravel, moist to wet, soft to firm
GM
SILTY GRAVEL: light yellowish brown, fine to coarse sand, trace clay, well graded, wet, soft
GP
SANDY GRAVEL: light yellowish brown, fine sand, rounded to sub-rounded gravel, max. size 5.0cm, some silt, moist, soft to firm
SP
GRAVELLY SAND: coarse, light brownish grey, decreasing gravel content and size grading downcore, with silt, moist, soft
SW
SAND: coarse, light yellowish brown, some gravel, with silt, trace clay, moist, soft
SAND: coarse, light yellowish brown, with clay, some silt, some gravel,



Notes:

- for 5' cores, percent recovery based on a total core length of 1.524m
- developed February 22, 2007 with a Monsoon pump
- pumped water until clear; total water pumped 225L
- well is down and around driveway into the back left corner of farmers field on left of Curry Rd.
- water level measured from top of PVC pipe, stickup: 0.84m
- sand came up into casing to 45' after putting in holeplug
- lots of sand pushing up into casing; high pressure at this location
- had 40' of sand pushed up into casing when drilling

WO75-S (Monitoring Well)

University of Waterloo

Date Drilled: January 10, 2007
Drilling Inspector: Joanna Passmore
Drillers: Boart Longyear - SDS Drilling
Method: Rotosonic Mini Sonic Drill Rig 4x6" system
Total Depth of Boring: 10.67m
Depth to water: 5.57mbgs (NAD83) (Measured March 29, 2007)
Ground Elevation: 302.70masl (NAD83)
Top of PVC riser elevation: 303.62m (NAD83)
Location: UTM17 North 4770112.00m, East 520015.09m
Originally Surveyed: March 28, 2007
Survey Corrected: June 22, 2007
Installation: - 2.00" Schedule 40 PVC riser and screen
- holeplug from 4.57mbgs to 7.92mbgs
- screen from 8.84mbgs to 10.36mbgs
- sand pack from 7.92mbgs to 10.67mbgs
- grout from 0mbgs to 4.57mbgs
Logged By: Geoff Moroz, Jaqueline Kreller
Last Updated: June 25, 2007

USCS = Unified Soil Classification System
mbgs = Metres Below Ground Surface
masl = Metres Above Sea Level

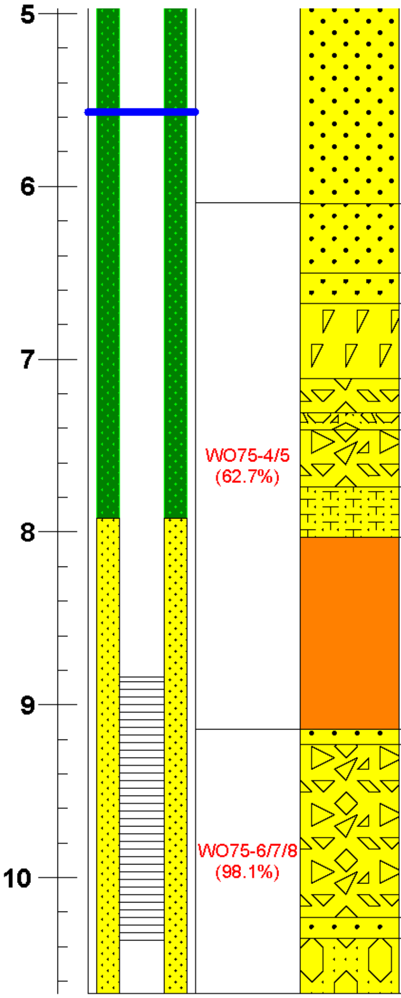
Well Construction Legend:

- Well Screen
- Water Level
- Hole Plug
- Bentonite Grout
- Sand pack

Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
0				Pt	TOPSOIL: dark brown, moist, some gravel
1–3		WO75-1 (52.5%)		SM-GM	SANDY SILT: olive brown, fine to medium sand, with gravel, moist to wet, soft
3				SM	SANDY SILT: light olive brown, medium sand, some clay, some gravel, moist to wet, soft
				SW	SAND: coarse, light olive brown, with silt, some gravel, moist, soft
				SW	
4				SM-GM	SAND: medium to coarse sand, light olive brown, with silt, with gravel, some solid lenses of clay, moist, soft
				SP	SANDY GRAVELLY SILT: light olive brown, rounded to sub-angular gravel, trace cobbles, max. size 7.0cm, mostly fairly large gravel, fine sand, dry, soft
5		WO75-2/3 (62.7%)			SAND: medium, light olive to olive brown, dry, soft

WO75-S (Monitoring Well)

Depth (m) | Well Construction | Core No. and % Recovery | Lithology



USCS	Lithological Description
SW	SAND: medium, light yellowish brown, with clay, some rounded to sub-angular gravel, max. size 2.5cm, dry, soft
SP	SAND: medium, light yellowish brown, some silt, some clay, moist, soft
SP	SAND: medium to coarse, light yellowish brown, with gravel, some silt, moist, some dry bits, soft
GW	SANDY SILTY GRAVEL: light olive brown, rounded to sub-rounded, max. size 6.0cm, moist, soft to firm
SW	GRAVELLY SAND: medium, light yellowish brown, rounded gravel, max. size 6.5cm, moist, loose
GP	GRAVEL: light greyish brown, trace coarse sand, rounded to sub-angular gravel, trace silt, moist, loose
SW	GRAVELLY SAND: medium, light olive brown, rounded to sub-angular gravel, max. size 6.5cm, trace silt, moist, loose
SM	SILTY SAND: medium, light olive brown, with rounded to angular gravel, some clay, decreasing to no clay downcore, moist, soft
MISS.	MISSING
SP	SAND: coarse to medium, light olive brown, with clay, with gravel, moist, soft
SW	GRAVELLY SAND: coarse to medium, light olive brown, with silt, some cobbles, max. size 10.0cm, trace clay, moist to wet, soft
SP	SAND: coarse, olive brown, some silt, some rounded gravel, max. size 4.0cm, moist, soft
GW	SANDY GRAVEL: pale yellow, medium to coarse sand, some clay/silt, round to angular, trace cobbles, max. size 11.0cm, moist, soft to firm

Notes:
- for 5' cores, percent recovery based on a total core length of 1.524m
- developed February 22, 2007 with a Monsoon pump
- pumped water until clear; total water pumped 165L
- well is down and around driveway into the back left corner of farmers field on left of Curry Rd.
- water level measured from top of PVC pipe, stickup: 0.93m
- sand came up into casing to 45' after putting in holeplug
- lots of sand pushing up into casing; high pressure at this location
- had 40' of sand pushed up into casing when drilling

WO76 (Monitoring Well)

Date Drilled: January 14, 2007
Drilling Inspector: Joanna Passmore
Drillers: Boart Longyear - SDS Drilling
Method: Rotosonic Mini Sonic Drill Rig 4x6" system
Total Depth of Boring: 42.67m
Depth to water: 30.47mbgs (NAD83) (Measured April 9, 2007)
Ground Elevation: 332.79masl (NAD83)
Top of PVC riser elevation: 332.97m (NAD83)
Location: UTM17 North 4769424.85m, East 519338.21m
Originally Surveyed: March 28, 2007
Survey Corrected: June 22, 2007
Installation: - 2.00" Schedule 40 PVC riser and screen
- holeplug from 30.48mbgs to 34.29mbgs & 38.10mbgs to 42.67mbgs
- screen from 35.05mbgs to 38.10mbgs
- sand pack from 34.29mbgs to 38.10mbgs
- grout from 0mbgs to 30.48mbgs
Logged By: Geoff Moroz, Jaqueline Kreller
Last Updated: June 25, 2007

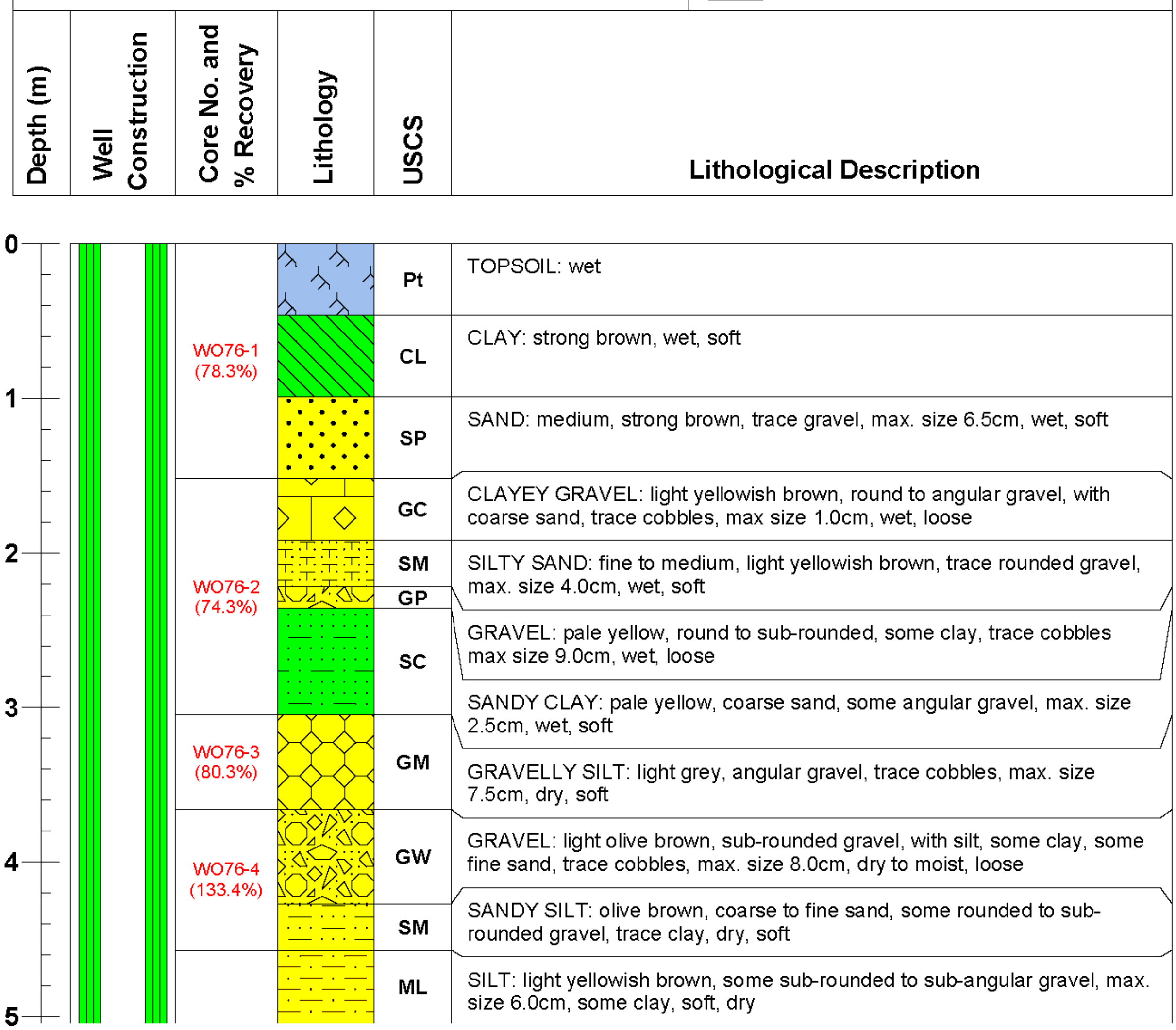
USCS = Unified Soil Classification System

mbgs = Metres Below Ground Surface

masl = Metres Above Sea Level

Well Construction Legend:

Well Screen
Water Level
Hole Plug
Bentonite Grout
Sand pack



WO76 (Monitoring Well)

Core No. and % Recovery	USCS	Lithological Description
WO76-5 (91.4%)	SP	SAND: fine to medium, light yellowish brown, with silt, grading to silty sand downcore, some clay downcore, soft, dry
WO76-6 (102.0%)	SP	SAND: fine, light olive brown, trace silt, dry to moist, soft
WO76-7 (78.3%)	SP	SAND: fine to medium, light yellowish brown, trace clumps of silt, dry, soft
WO76-8 (75.0%)	SP	SAND: medium, light yellowish brown, with silt, moist, soft
WO76-9 (88.2%)	ML	SILT: light yellowish brown, some hard chunks (till-like), trace gravel, sub-rounded, max. size 6.0cm, dry, soft
	SP	SAND: fine, light yellowish brown, some silt, dry, soft
WO76-10 (85.5%)	SP	SAND: fine to coarse, light olive brown, moist, loose
	SM	SILTY SAND: fine, light olive brown, moist, soft

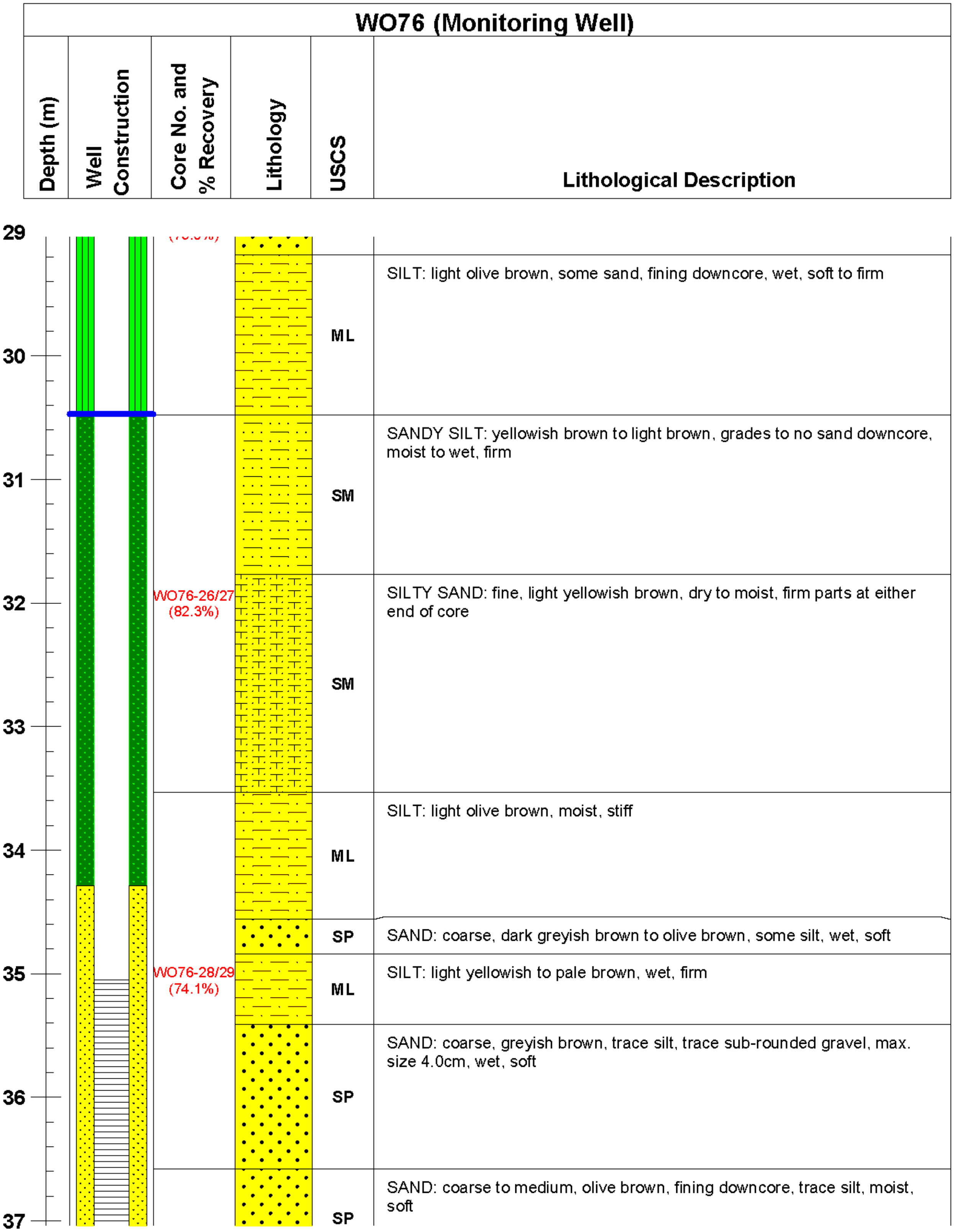
WO76 (Monitoring Well)

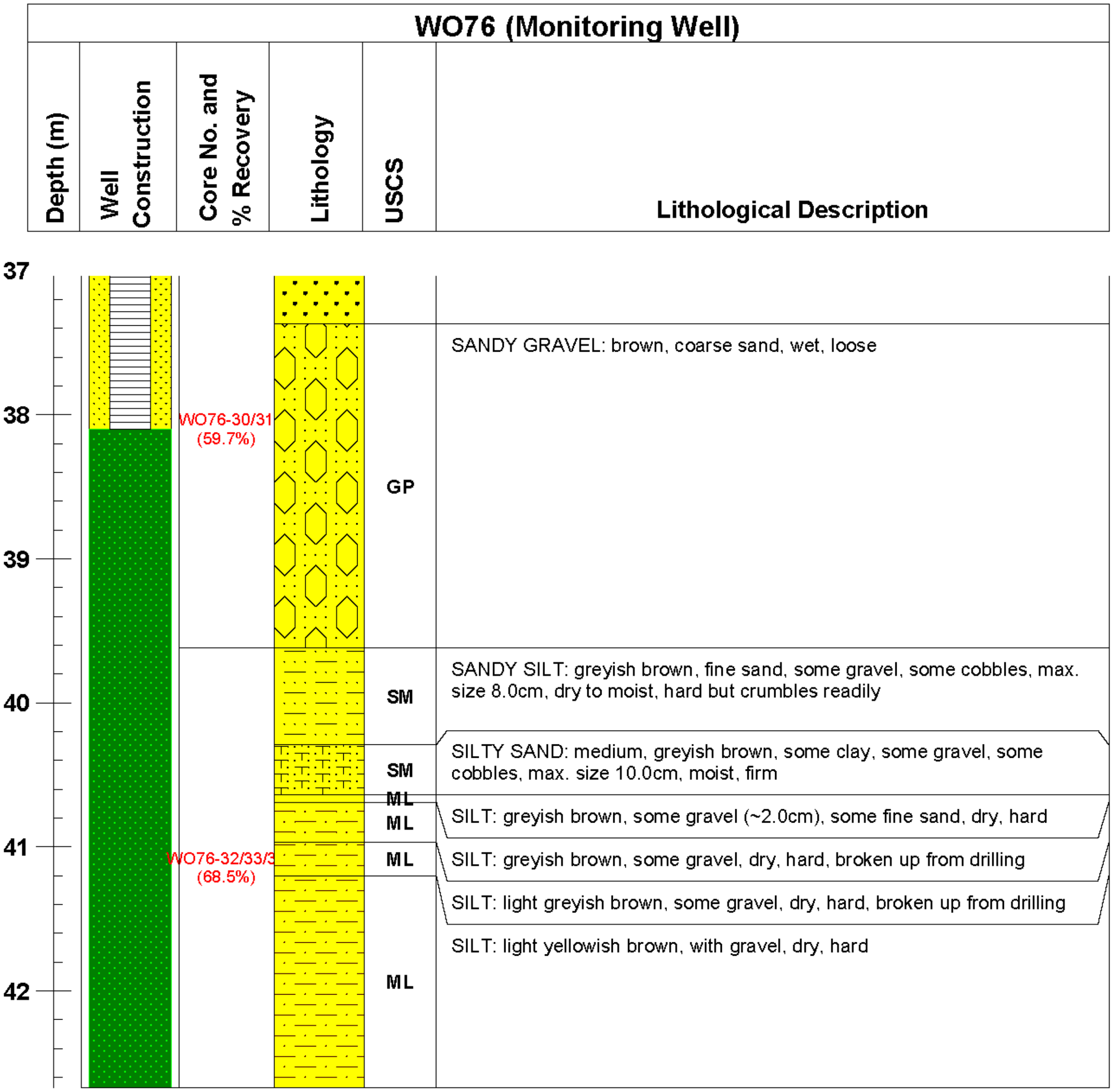
Depth (m)	Well Construction	Core No. and % Recovery	Lithology	USCS	Lithological Description
13				SM	SANDY SILT: light yellowish brown, trace gravel, moist
14		WO76-11 (145.9%)		SP	SAND: fine, light yellowish brown, some to trace silt, dry to moist, soft
15		WO76-12 (101.8%)		SP	SAND: medium, light yellowish brown, some rounded gravel, max. size 6.5cm, dry, soft
		WO76-13 (138.2%)		SP	SAND: medium, light yellowish brown, with silt, grading to sand with clay downcore, wet, soft
16		WO76-14 (100.1%)		SP	SAND: medium, light olive brown, trace silt, moist to dry, soft
				SP	SAND: medium, light olive, some hard silt chunks (possibly broken up till), moist to dry, soft
17		WO76-15 (83.6%)		SP	SAND: fine to medium, light olive brown, some gravel, larger broken up pieces indicate that sediment was compact prior to drilling; likely a compact TILL aquitard, dry, loose
18				SP	SAND: fine to medium, light olive brown, moist to dry, soft
		WO76-16 (131.4%)		SM	SILTY SAND: medium, light yellowish brown, moist to wet, soft, soupy and siltier downcore
19		WO76-17 (78.3%)		SP	SAND: fine to medium, light olive brown, moist to dry, soft
20				SP	SAND: fine to medium, light olive brown, with silt lumps approximately 2.0cm in diameter, moist to dry, soft
21		WO76-18 (87.0%)		SM	SILTY SAND: fine to coarse, light olive brown, till-like compact chunks, likely broken up during drilling, likely till aquitard, dry, loose

WO76 (Monitoring Well)

Core No. and % Recovery	USCS	Lithological Description
	SP	SAND: medium to coarse, light olive brown, trace silt, moist, soft
	SM	SILTY SAND: fine to medium, light olive brown, some gravel (~5.0cm), moist, soft
	SM	SANDY SILT: light olive brown, fine sand, some gravel (~1.5cm), moist, soft
WO76-19/20 (70.5%)	SM	SANDY SILT: light yellowish brown, with gravel, blocky, dry, soft
	SP	SAND: fine, light olive brown, some silt, moist to dry, soft
	SM	SILTY SAND: coarse, light olive brown, some clay, some gravel (~1.0cm), moist, soft
	SC	SANDY CLAY: light brownish grey, with gravel, max. size 4.0cm, moist, soft
WO76-21/22/2 (73.8%)	SM	SILTY SAND: fine, light yellowish brown, small layers of more silty material, moist, soft
	ML	SILT: light yellowish brown, trace amounts of light brownish grey clay lumps 2.0cm in diameter, moist to dry, loose
	ML	SILT: light olive brown, trace gravel (~0.75cm), wet to moist, soft to firm
	SP	SAND: medium, olive brown, with silt, silt content increases to ~50% gradually from 28.16 - 28.42m, trace gravel, wet to moist, soft to firm
WO76-24/25 (79.0%)	SP	SAND: fine to medium, light olive brown, with silt, fining downcore, moist, soft to firm

Depth (m): 21–29


WO76 (Monitoring Well)
Depth (m)
Well Construction
Core No. and % Recovery
Lithology
USCS
Lithological Description
29
30
31
32
33
34
35
36
37
WO76-26/27
(82.3%)
WO76-28/29
(74.1%)
ML
SILT: light olive brown, some sand, fining downcore, wet, soft to firm
SM
SANDY SILT: yellowish brown to light brown, grades to no sand downcore, moist to wet, firm
SM
SILTY SAND: fine, light yellowish brown, dry to moist, firm parts at either end of core
ML
SILT: light olive brown, moist, stiff
SP
SAND: coarse, dark greyish brown to olive brown, some silt, wet, soft
ML
SILT: light yellowish to pale brown, wet, firm
SP
SAND: coarse, greyish brown, trace silt, trace sub-rounded gravel, max. size 4.0cm, wet, soft
SP
SAND: coarse to medium, olive brown, fining downcore, trace silt, moist, soft



Notes:

- for 5' cores, percent recovery based on a total core length of 1.524m
- developed February 9, 2007 with a Monsoon pump
- pumped water until clear; total water pumped 180L
- well is 880m in from Claus Well
- water level measured from top of PVC pipe, stickup: 0.18m

Appendix C: Supplementary Groundwater data

Table C.1. Hydraulic head contour plot raw data.

January 8, 2007 - Aquifer 2			
Well	Easting	Northing	Elevation (masl)
WO11-6	519657.022	4770436.411	300.050
WO35	519977.767	4770190.274	297.959
WO36	520061.883	4770308.647	298.949
WO37	519848.918	4770359.329	298.486
WO40	519548.205	4770560.160	299.795
WO62	519585.601	4770111.856	298.923

January 8, 2007 - Aquifer 3			
Well	Easting	Northing	Elevation (masl)
WO11-18	519657.076	4770436.567	299.985
WO56	519759.218	4769718.765	298.460
WO60	519407.673	4769959.042	300.364
WO61	519585.601	4770111.856	298.570
WO64	519883.684	4770191.358	297.443

May 21/22, 2008 - Aquifer 2			
Well	Easting	Northing	Elevation (masl)
WO11-6	519655.540	4770438.100	299.128
WO66	519684.343	4770484.023	298.931
WO37	519847.471	4770360.903	298.35
WO62	519920.735	4770427.858	298.415
WO36	520060.456	4770310.281	297.903
WO74-D	520056.136	4770155.969	297.714
WO74-WT	520052.329	4770152.747	297.718
WO75-S	520015.085	4770113.999	297.807
WO75-D	520013.592	4770112.036	294.756
WO40	519546.773	4770561.811	298.949
WO72-S	519792.667	4770580.006	298.589
WO73-D	519937.067	4770754.012	298.634
WO67	519488.267	4770318.108	300.025
WO35	519976.332	4770191.930	297.858
WO04-18	520114.388	4770381.168	297.793
WO12-8	520126.549	4769499.307	297.264

May 21/22, 2008 - Aquifer 3			
Well	Easting	Northing	Elevation (masl)
WO11-18	519655.540	4770438.100	299.228
WO63	519848.470	4770360.172	298.32
WO60	519406.187	4769960.682	301.211
WO56	519758.467	4769720.313	298.093
WO58	519343.953	4769789.942	302.017
WO71-S	519048.833	4770551.409	309.532
WO71-D	519049.966	4770550.171	309.706
WO61	519584.084	4770113.481	299.86
WO69	518627.499	4769467.583	303.367
WO70	518180.752	4769744.761	303.532
WO64	519882.245	4770192.991	298.023
WO12-19	520126.549	4769499.307	297.276
WO68	519231.127	4770032.888	301.776
WO76	519338.213	4769424.852	302.446

Appendix D: Geochemistry at Recharge Stations

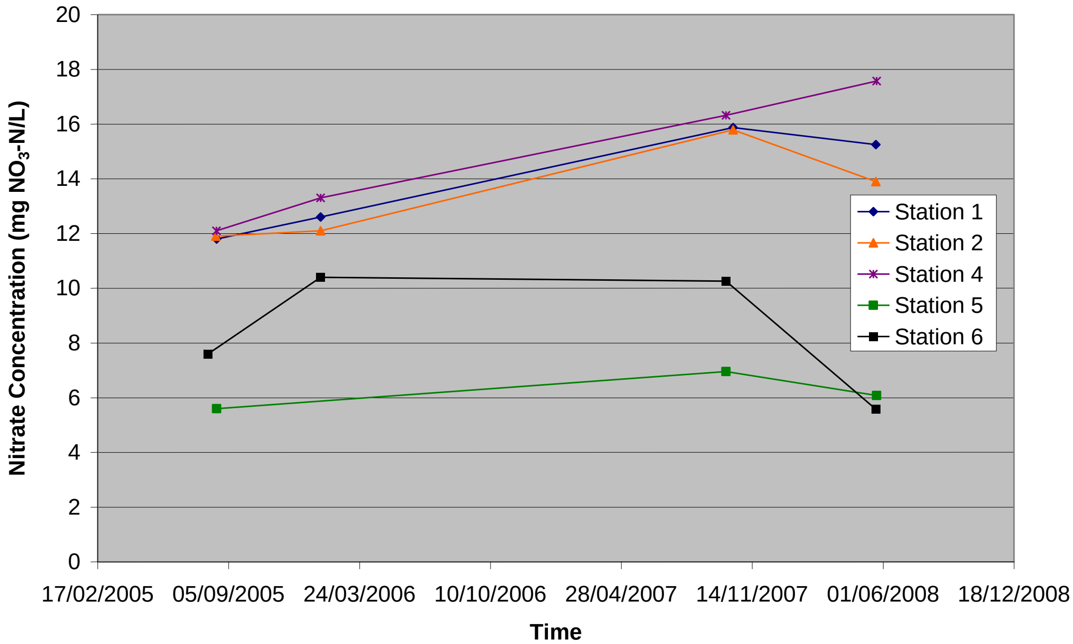


Figure D.1. Nitrate concentration (mg NO_3-N/L) at stations 1, 2, 4, 5, 6.

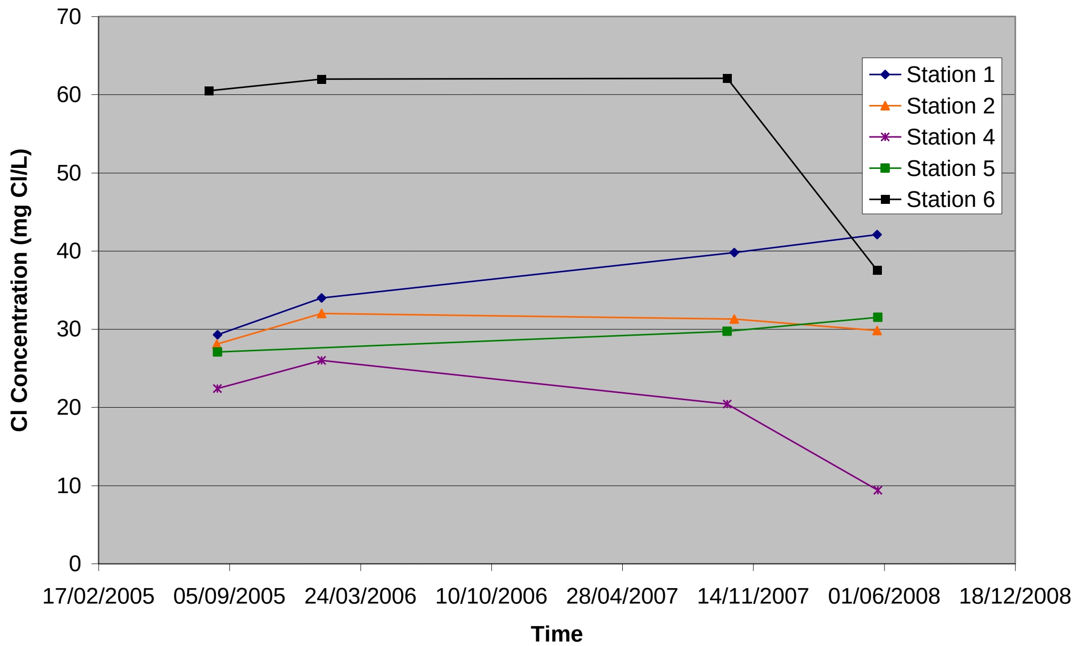


Figure D.2. Chloride concentrations (mg/L) at stations 1, 2, 4, 5, 6.

Appendix E: Supplementary Temperature, Pressure and Nitrate Data

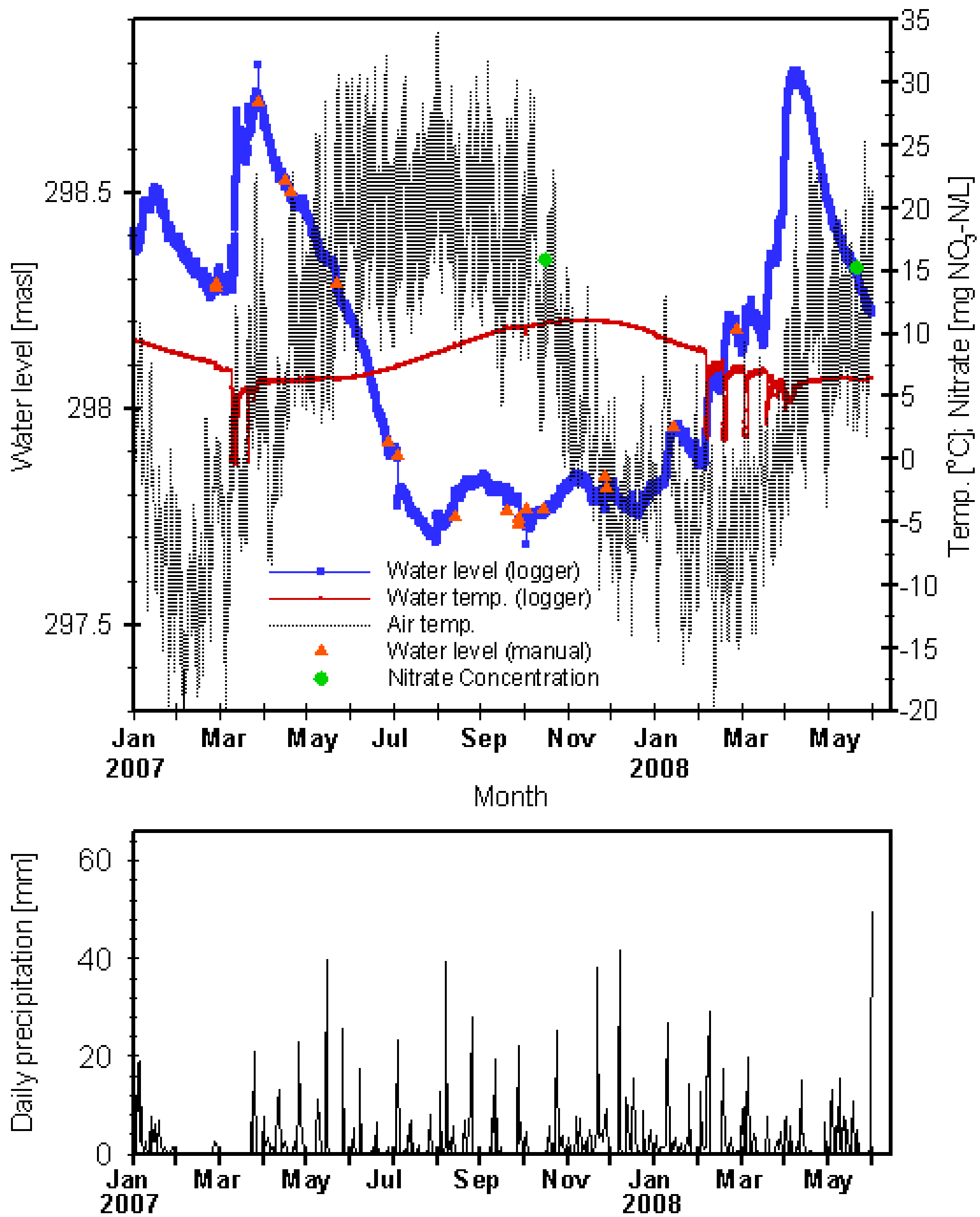


Figure E.1. Temperature, water level and nitrate concentration at station 1 (WO63).

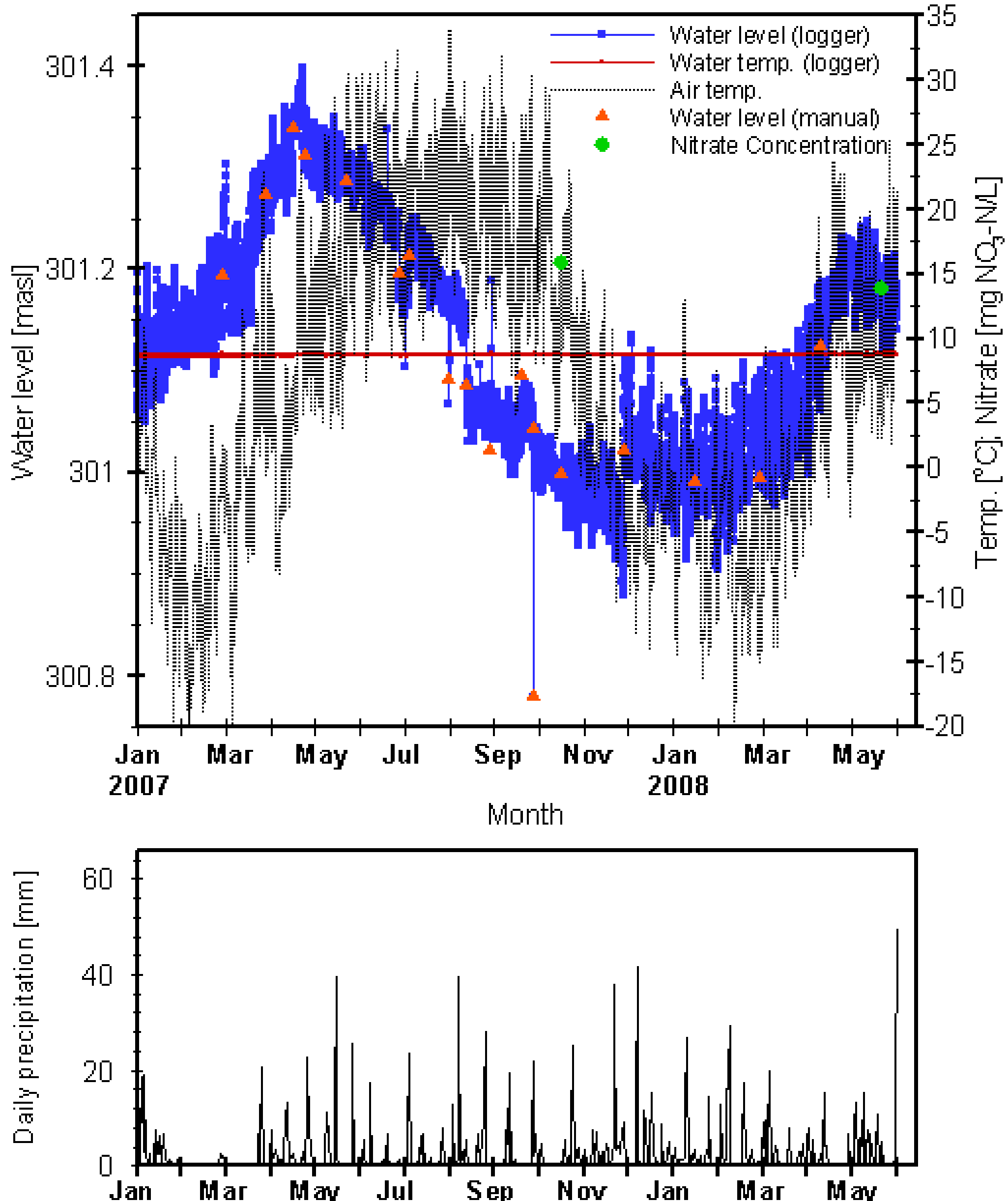


Figure E.2. Temperature, water level and nitrate concentration at station 2 (WO60).

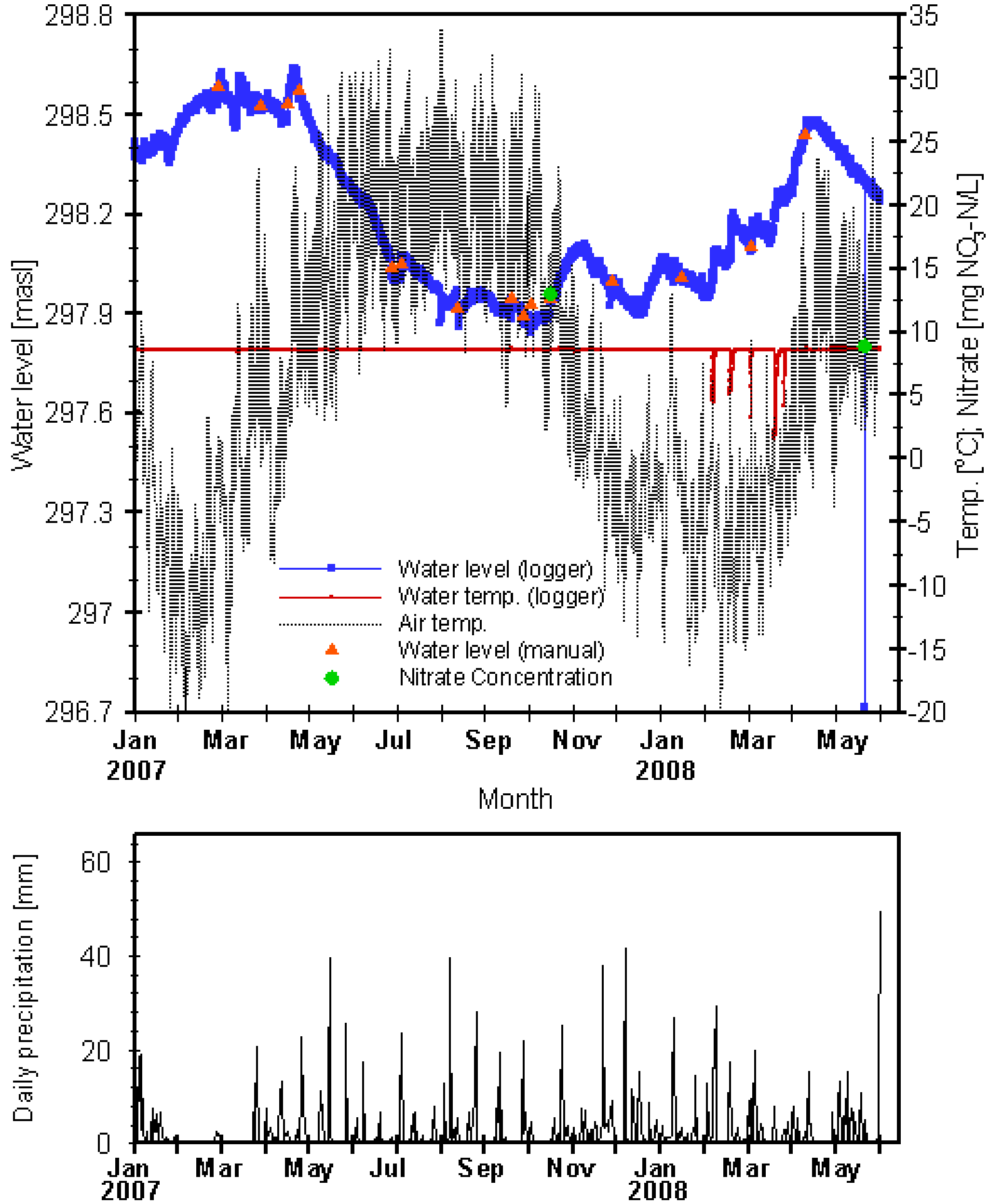


Figure E.3. Temperature, water level and nitrate concentration at station 3 (WO56).

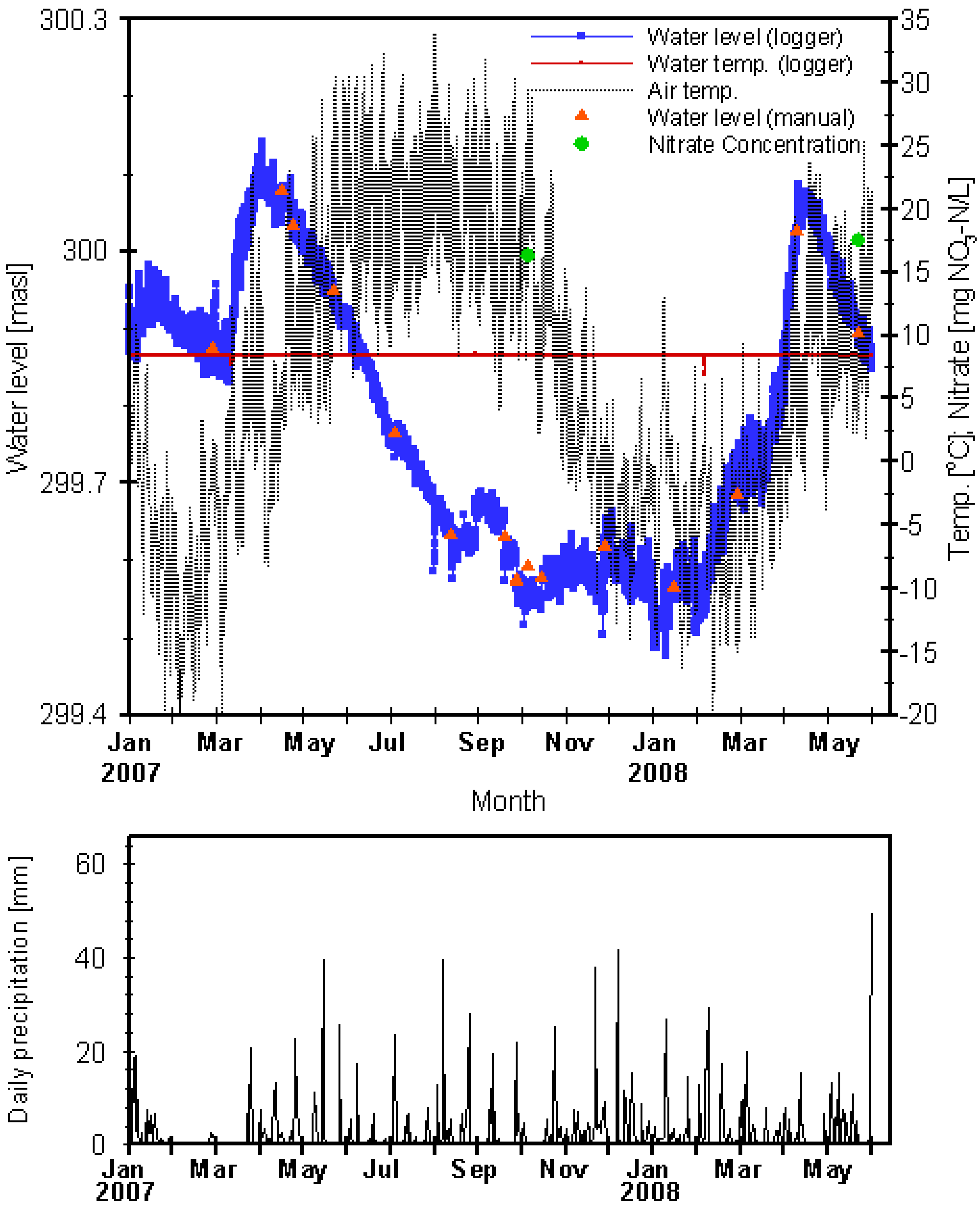


Figure E.4. Temperature, water level and nitrate concentration at station 4 (WO61).

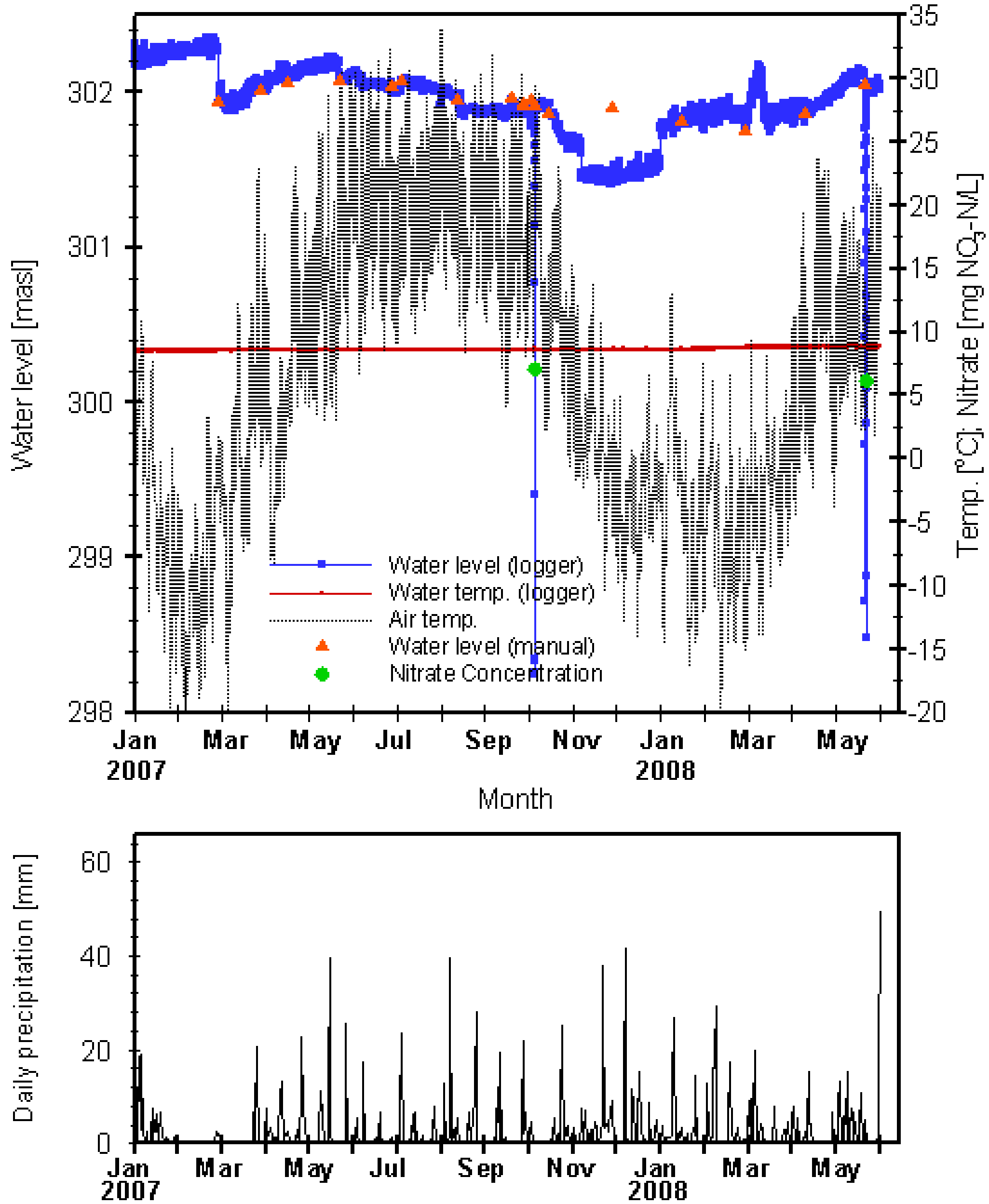


Figure E.5. Temperature, water level and nitrate concentration at station 5 (WO58).

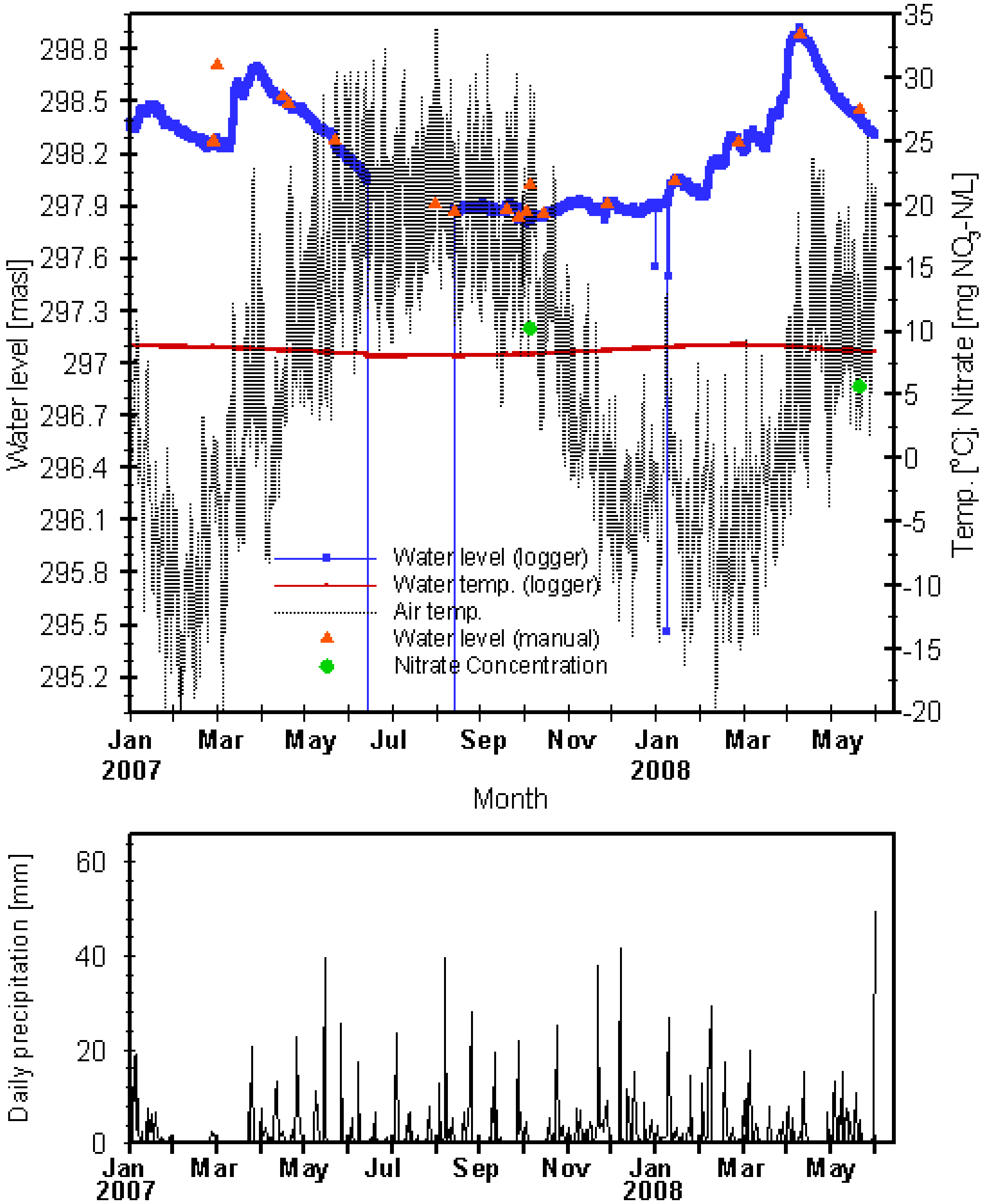


Figure E.6. Temperature, water level and nitrate concentration at station 6 (WO62).

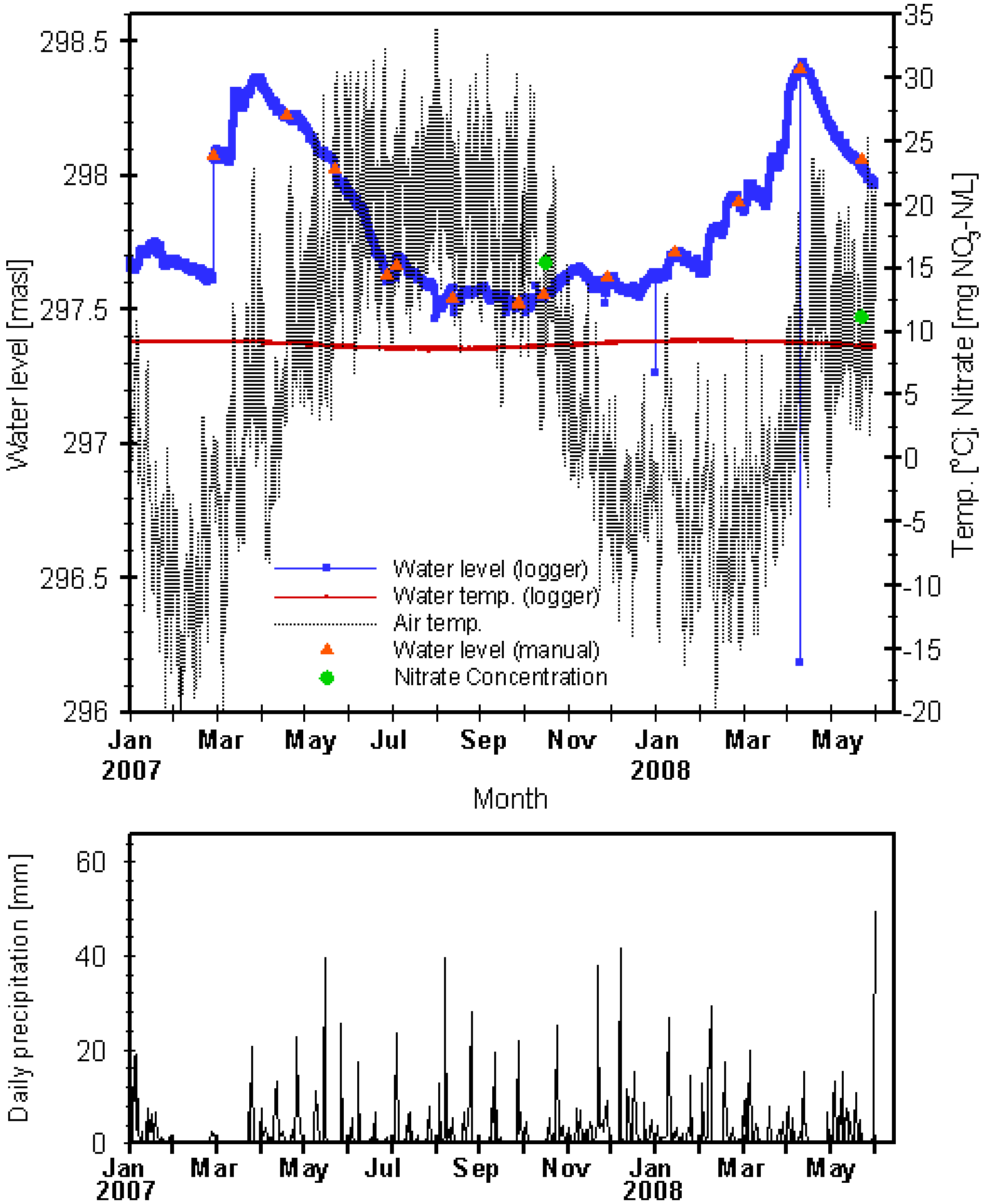


Figure E.7. Temperature, water level and nitrate concentration near station 8 (WO64).

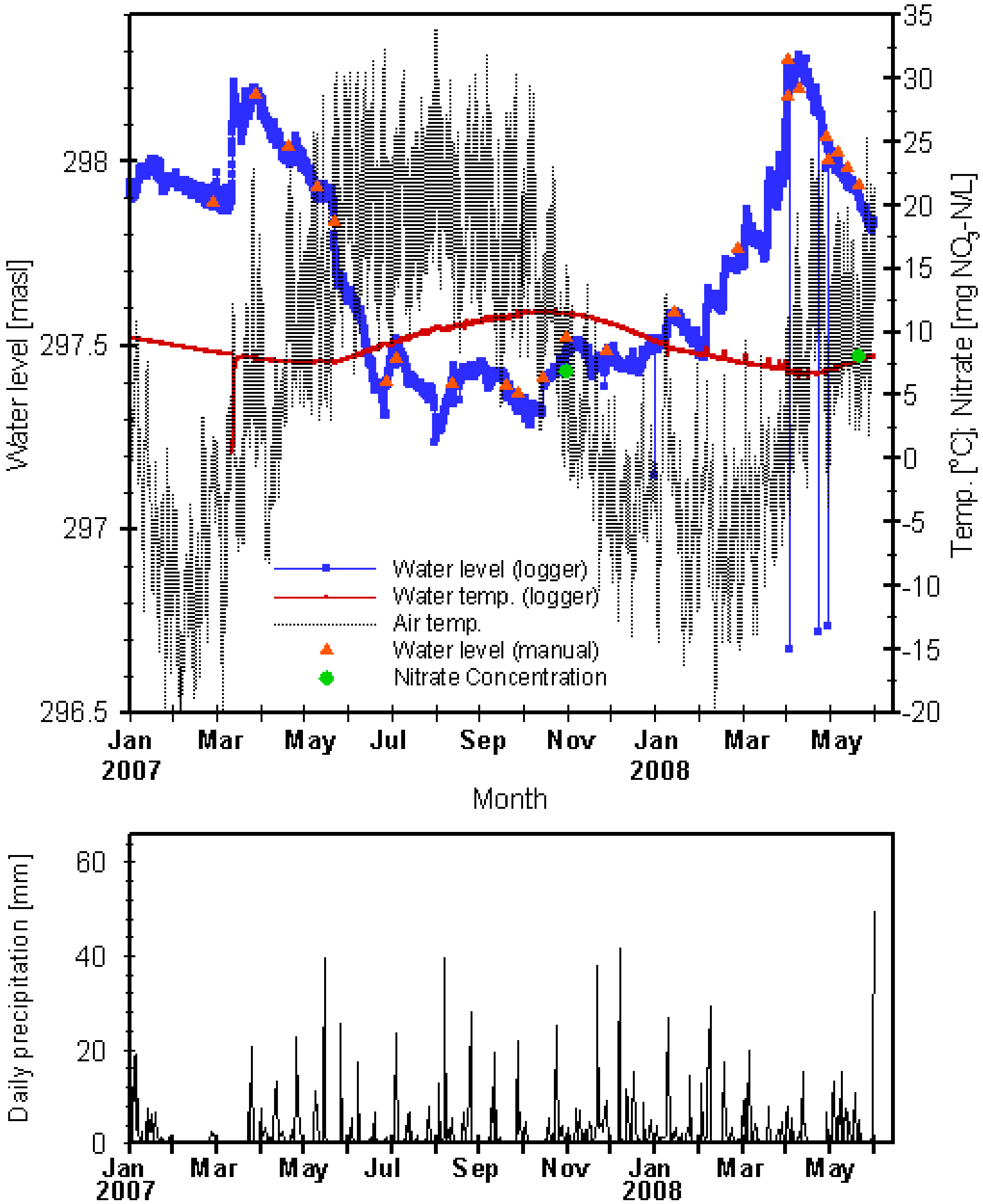


Figure E.8. Temperature, water level and nitrate concentration at station 9 (WO36).

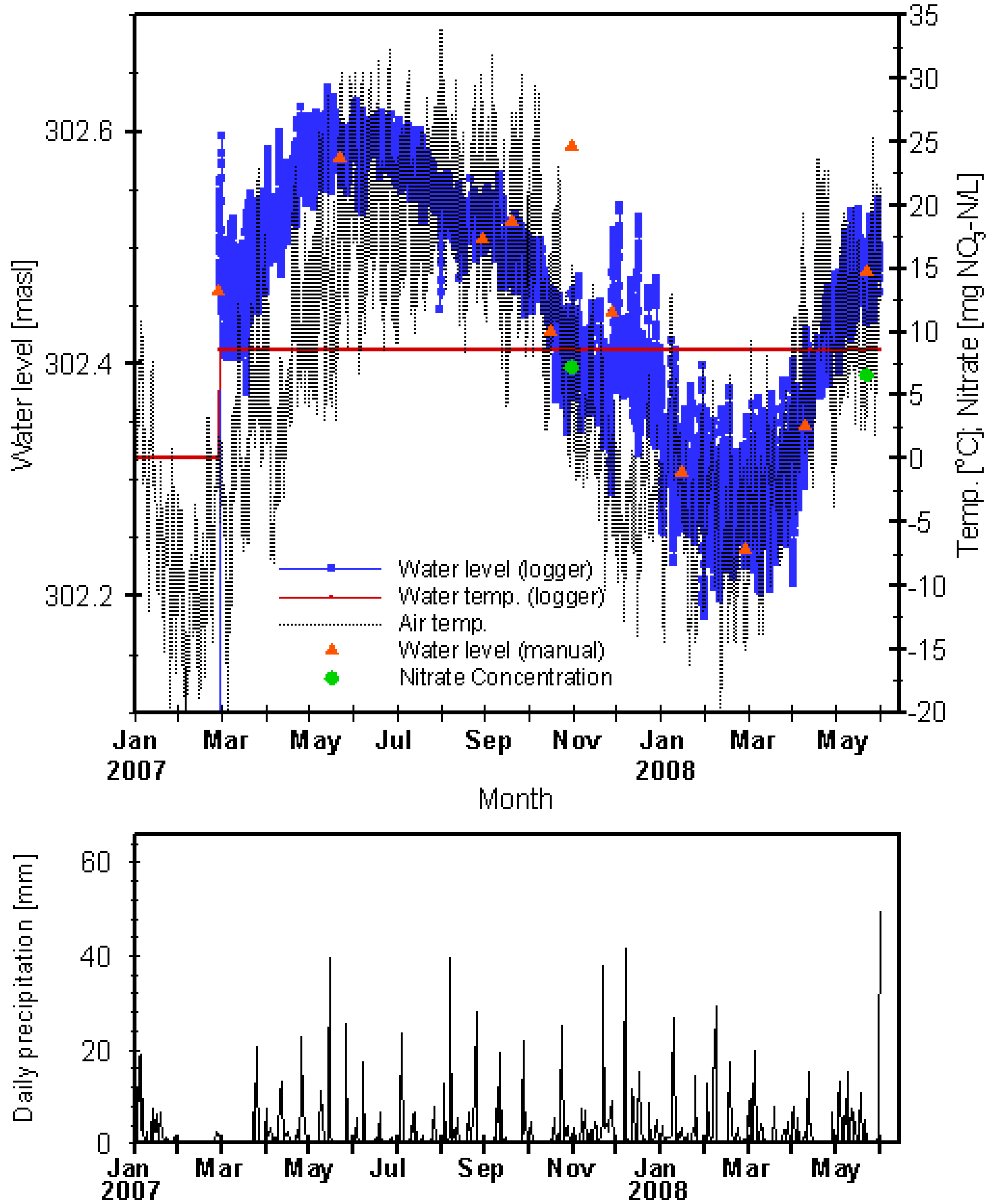


Figure E.9. Temperature, water level and nitrate concentration at stations 12 and 13 (WO76).

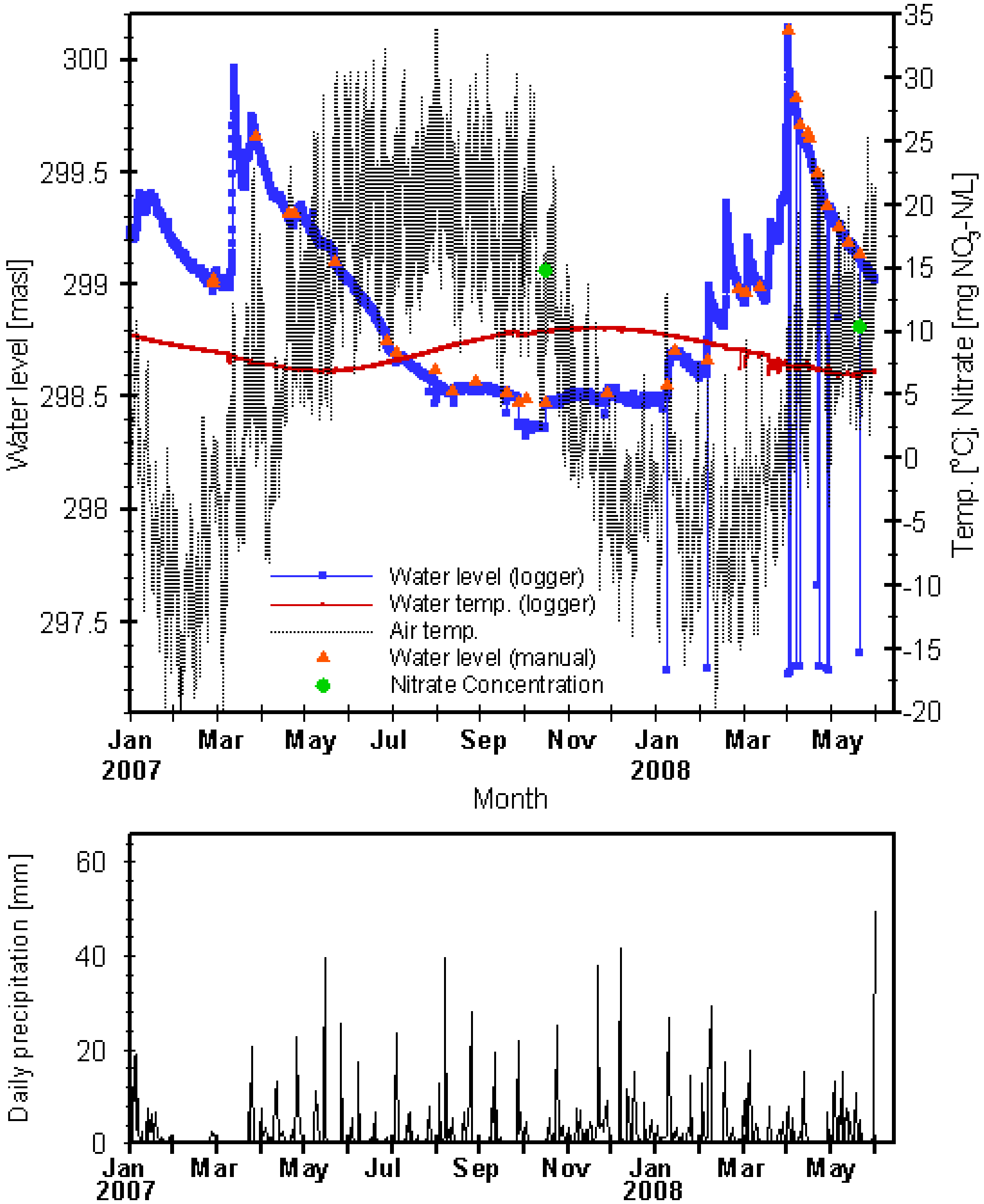


Figure E.10. Temperature, water level and nitrate concentration at WO11-6.

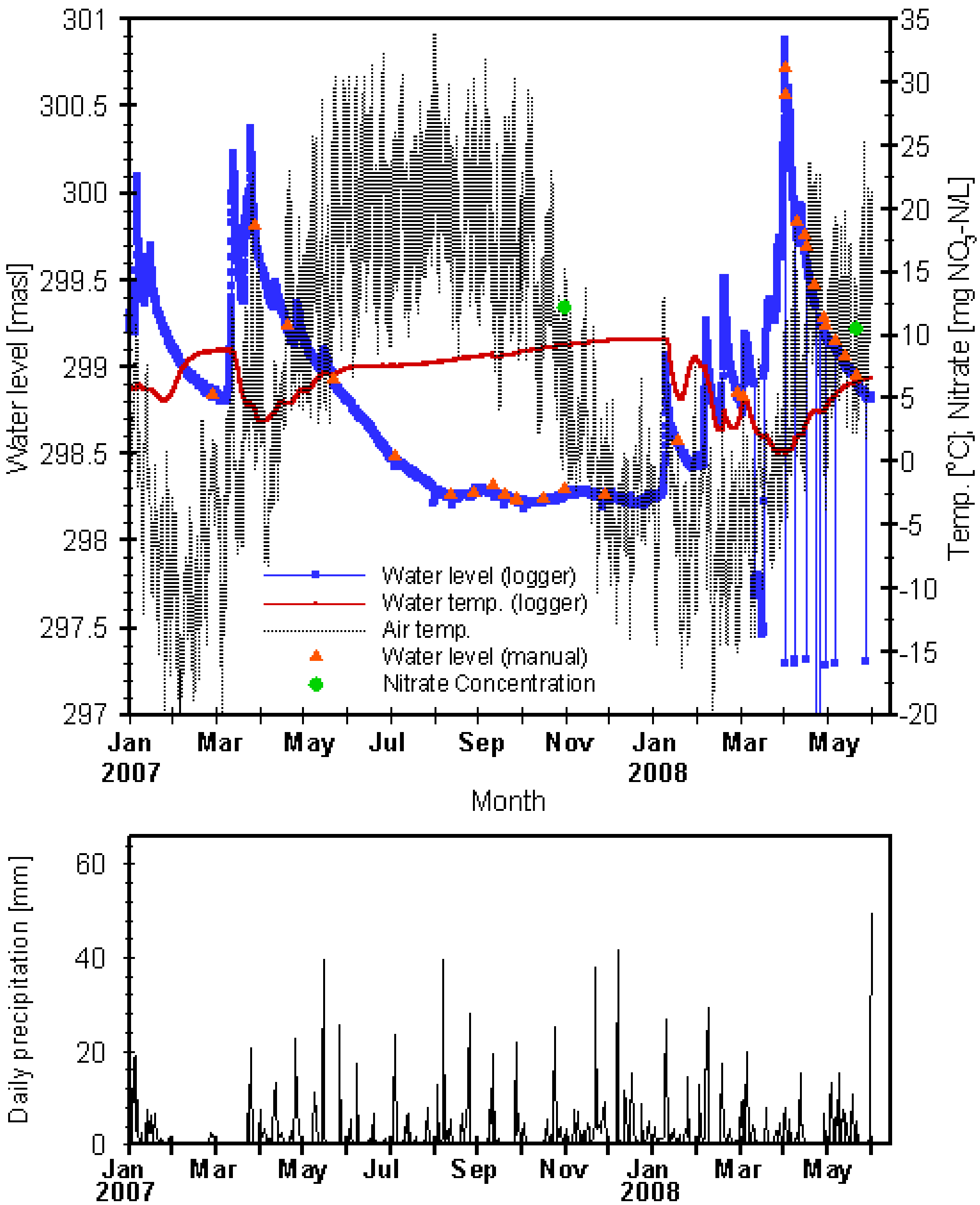


Figure E.11. Temperature, water level and nitrate concentration at WO40.

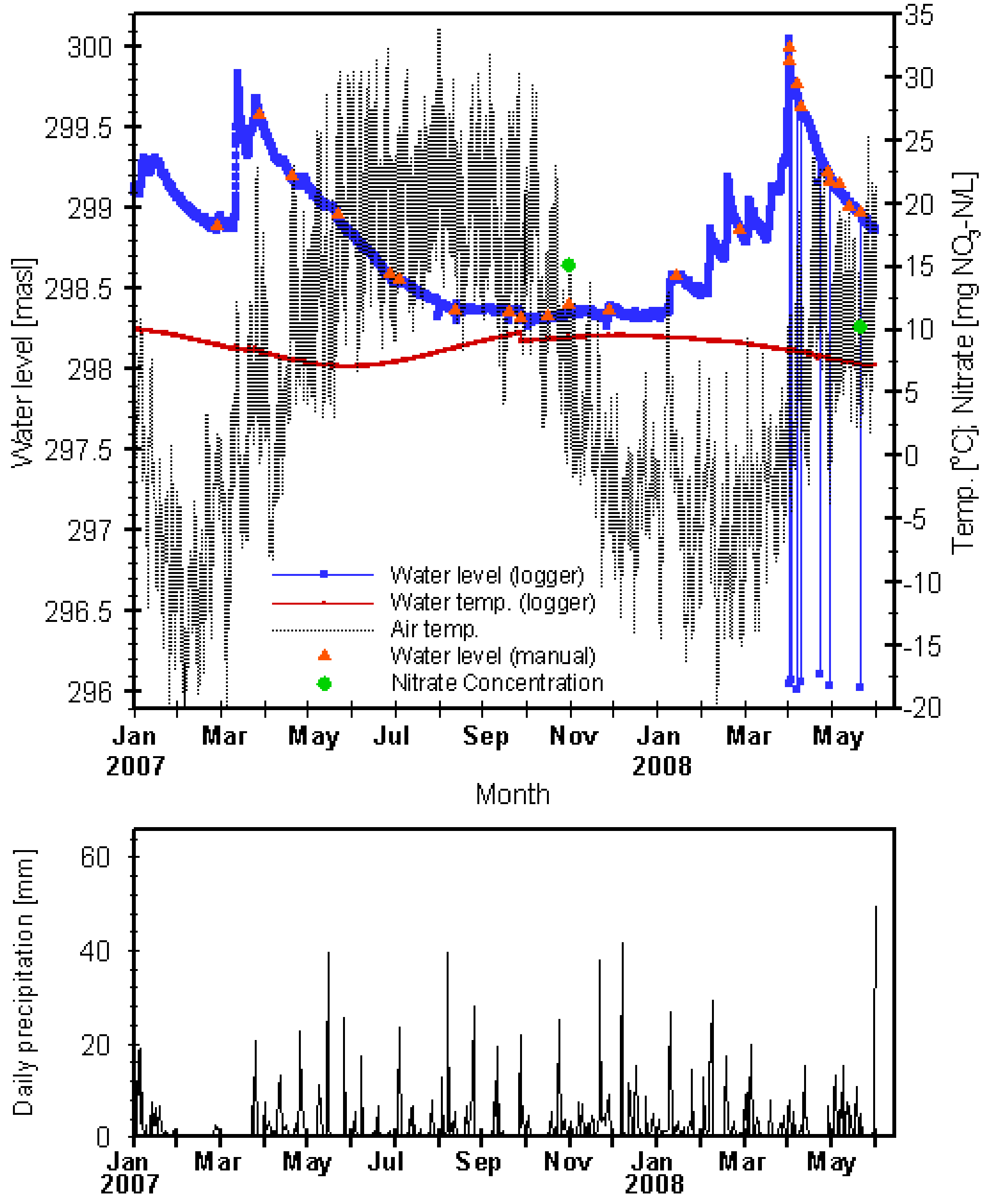


Figure E.12. Temperature, water level and nitrate concentration at WO66.

Appendix F: Description and Table of Soil and Water Quality Data

Station 8 generally had the highest measured concentrations. The bulk soil nitrate concentrations below the root zone typically ranged from 2 to 7 mg/kg in May 2007 which decreased to 1 to 3 mg/kg in May 2008. Average porewater nitrate concentrations decreased from 67.2 to 26.4 mg/L in May 2008. Within the top 1 metre, average bulk soil nitrate concentrations decreased from 26 mg/kg in May 2007 to 7 mg/kg in May 2008. The associated average porewater nitrate concentrations decreased from 60.3 to 18.4 mg/L with peak concentrations decreasing from 137.7 to 34.3 mg/L. Soil stratigraphy changes at about 1.6 mbgs from coarse to fine grained sediments. At this depth in both the soil cores, nitrate concentrations increased by about a factor of 2-3 throughout the entire fine grained layer.

Three stations are located within the glacial outwash channel. Station 6 bulk soil nitrate concentrations below the root zone ranged from non-detectable to 3.6 mg/kg in May 2007 which decreased to 0.1 to 1.7 mg/kg in May 2008. Peak porewater nitrate concentrations decreased from 109.6 to 65.3 mg/L. Above the root zone, peak soil nitrate values decreased from 22 to 16 mg/kg with associated peak porewater nitrate concentrations decreasing from 144.3 to 99.8 mg/L for the same time frame. At station 9 the only 2 cores taken were just 4 months apart, thus changes in concentrations may be due to the slight spatial variability as much as due to BMP effects. Below the root zone concentrations ranged from 0.1 to 0.6 mg/kg and from 1.5 to 15.1 mg/L in December 2007. Similarly in May 2008, values ranged from 0.2 to 1.1 mg/kg and from 3.1 to 11.6 mg/L. Near the surface, peak concentrations varied from 2.7 mg/kg and 99.4 mg/L in December 2007 to 13.4 mg/kg and 56.4 mg/L in May 2008. Station 1 had typical bulk soil nitrate concentrations below the root zone ranging from 0.2 to 0.5 mg/kg and associated porewater nitrate concentrations of 6.0 and 16.1 mg/L in May 2007 and 2008 respectively. Comparatively, peak values of 9.9 and 4.2 mg/kg in May 2007 and 2008 respectively and porewater nitrate concentrations of 49.2 and 16.1 mg/L were observed above the root zone.

Station 3 had peak bulk soil nitrate concentrations in May 2007 of 0.3 mg/kg below the root zone and 19.7 mg/kg above. The peak and average porewater nitrate concentrations above the root zone were 111.6 and 23.9 mg/L which decreased to 1.3 and 1.1 mg/L below. A year later, the near surface and deeper peak bulk soil nitrate concentrations were 0.6 and 8.9 mg/kg respectively with peak porewater nitrate concentrations decreasing to 42.9 and 8.0 mg/L respectively.

At station 5 in May 2007, average bulk soil nitrate concentrations were 0.5 and 4.5 mg/kg below and above the root zone respectively. The associated average porewater nitrate concentrations were 4.1 and 27.2 mg NO_3^--N/L. Similar results were observed at station 7 in May 2007. Average bulk soil nitrate concentrations were 0.4 and 5.1 mg/kg below and above the root zone respectively. The associated average porewater nitrate concentrations were 4.9 and 28.7 mg NO_3^--N/L. At each of these stations, concentrations were fairly constant with depth below the root zone to total coring depths of 5.5 and 5.7 mbgs respectively.

In May 2007 in the station 4 root zone, bulk soil nitrate concentrations ranged from 0.8 to 28.4 and averaged 7.0 mg/kg with the associated porewater nitrate concentration ranging 7.6 to 141.8 and averaged 36.4 mg/L. Bulk soil nitrate concentrations in May 2008 ranged from 0.8 to 12.2 and averaged 4.8 mg/kg and the associated porewater nitrate concentrations ranged from 6.4 to 56.6 and averaged 23.1 mg/L. Below 1 mbgs, in May 2007, bulk soil nitrate and porewater nitrate concentrations were nearly constant with depth and averaged 0.8 mg/kg and 11.2 mg/L respectively. Little changed a year later, as bulk nitrate and porewater nitrate concentrations averaged 0.8 mg/kg and 10.3 mg/L respectively.

Nitrate concentrations were fairly steady with time and depth beneath the top soil at station 2. This is likely due to the fact that cores didn't quite penetrate below about 4 mbgs, above which the clay-silt till layer dominates. Within this till layer, gravimetric water contents were nearly constant at about 10%. Below the root zone in May 2007, average bulk soil nitrate and porewater nitrate concentrations below 1 mbgs were 1.1 mg/kg and 11.6 mg/L respectively. After one year, these remained steady at 1.1 and 11.1 mg/L. Notable decreases in peak bulk soil and porewater nitrate concentrations were detected above the root zone. Respectively these values decreased in May 2007 from 25.2 mg/kg and 137.3 mg/L to 9.3 mg/kg and 40.9 mg/L in May 2008.

As mentioned earlier, stations 9-15 were only cored about 4 months apart. As a result, it is especially difficult to determine if changes in nitrate concentrations are due to changes in surface nitrate application or due to local spatial variability. Of these seven locations, only stations 9 and 12 are within the Parcel B which is under the influence of a BMP.

Station 10 average bulk soil nitrate and porewater nitrate concentrations were quite stable with time and depth. In the top 1 metre, respectively these values increased from 0.3 mg/kg and 3.5 mg/L in December

2007 to 1.3 mg/kg and 7.4 mg/L in May 2008. Below the root zone, these values decreased from 0.3 mg/kg and 6.1 mg/L to 0.2 mg/kg and 2.5 mg/L. Similar results were measured at station 11. Average bulk soil nitrate and porewater nitrate concentrations above the root zone increased slightly in December 2007 from 1.8 mg/kg and 8.7 mg/L to 2.0 mg/kg and 11.2 mg/L in May 2008. Below the root zone, these values increased in December 2007 from 0.6 mg/kg and 6.1 mg/L to 2.0 mg/kg and 21.0 mg/L in May 2008. In the May 2008 core, nitrate concentrations increased by about four times from about 2.2 to 3.9 mbgs. In the December 2007 core, several higher concentrations were also measured within this same depth range. At about 3.9 mbgs, the stratigraphy changes from sandy silt which begins near the surface to sandy clayey silt.

Station 12 average bulk soil nitrate and porewater nitrate concentrations varied above the root zone in December 2007 from 3.0 mg/kg and 12.3 mg/L to 2.3 mg/kg and 17.5 mg/L in May 2008. Respectively, these values remained nearly steady from 0.3 mg/kg and 6.7 mg/L to 0.4 mg/kg and 7.1 mg/L below the root zone. At station 13, located just metres away from station 12, both cores had low nitrate concentrations except for one sample within the top soil that peaked at 10.1 mg/kg and 37.9 mg/L in December 2007 and 22.3 mg/kg and 91.8 mg/L in May 2008 respectively. The rest of the cores had average concentrations varying from 0.4 mg/kg and 9.9 mg/L to 0.5 mg/kg and 6.2 mg/L. Nitrate concentrations increased about 5 times in the May 2008 core in the eight samples from 5.0 to the end of the core at 6.3 mbgs. The December 2007 core was only able to be completed to 2.5 mbgs so no comparison can be made.

Bulk soil nitrate and porewater nitrate at station 14 in December 2007 had two very high peaks in the top soil of 30.0 mg/kg and 128.2 mg/L and 13.6 mg/kg and 86.0 mg/L. Aside from these, the average bulk soil nitrate concentrations throughout the rest of the core ranged from 0.1 to 6.3 and averaged 1.8 mg/kg. The associated porewater nitrate concentrations ranged from 2.1 to 55.6 and averaged 19.6 mg/L. The May 2008 core did not contain an exceptionally high nitrate concentration near surface. In the top 1 metre, concentrations ranged from 3.0 to 7.7 and averaged 4.7 mg/kg with porewater nitrate ranging from 13.2 to 29.0 and averaging 18.7 mg/L. Below the root zone, bulk soil nitrate ranged from non-detectable to 3.9 and averaged 1.2 mg/kg and porewater nitrate ranged from non-detectable to 35.9 and averaged 12.0 mg/L.

Station 15 in December 2007 had fairly constant bulk soil nitrate and porewater nitrate concentrations above the root zone averaging 2.8 mg/kg and 12.7 mg/L. Below the root zone bulk soil nitrate ranged from 0.3 to 1.7 and averaged 0.6 mg/kg with the associated porewater nitrate ranging from 2.8 to 30.5 and averaging 10.9 mg/L. In May 2008, these values remained fairly constant except for one peak in the top soil of 15.0 mg/kg and 71.3 mg/L. Except for this peak, the average in values above the root zone was 1.9 mg/kg and 9.3 mg/L. Below 1 mbgs, the concentrations averaged 0.6 mg/kg and 8.5 mg/L.

Lastly, measurement of all samples collected across the entire study site yielded an average soil bulk density of 1.6 g/cm^3.

Soil bromide, nitrate, gravimetric water content (GWC) and volumetric water content (θ_v). Non-detectable results designated "<D.L."

Log ID	Station	Sample Midpoint Depth (m)	Soil NO_3-N (mg/kg)	Soil Br (mg/kg)	Soil Cl (mg/kg)	θ_g (g water/ g soil)	θ_v (g water/ cm^3 soil)	Soil Bulk Density (g/cm^3)
MAY 2007								
TH22								
TH22-1-1	Station 1	0.09	0.00	0.72		0.27	0.23	0.85
TH22-1-2	Station 1	0.24	9.88	0.75		0.24	0.23	0.96
TH22-2-1	Station 1	0.33	2.76	6.69		0.18	0.26	1.43
TH22-2-2	Station 1	0.57	2.55	7.29		0.05	0.05	1.00
TH22-2-3	Station 1	0.83	1.22	0.21		0.04	0.06	1.48
TH22-3-1	Station 1	1.57	0.29	<D.L.		0.05	0.08	1.68
TH22-3-2	Station 1	1.77	0.18	0.26		0.05	0.07	1.43
TH22-4-1	Station 1	2.22	0.11	0.27		0.07	0.10	1.41
TH22-4-2	Station 1	2.39	0.18	<D.L.		0.08	0.14	1.86
TH22-5-1	Station 1	3.31	0.19	<D.L.		0.07	0.13	1.83
TH22-6-1	Station 1	4.10	0.35	<D.L.		0.10	0.12	1.21
TH27								
TH27-1-1	Station 2	0.06	<D.L.	0.57		0.16	0.25	1.56
TH27-1-2	Station 2	0.20	25.23	11.44		0.18	0.30	1.62
TH27-1-3	Station 2	0.34	9.73	37.35		0.32	0.46	1.45
TH27-2-1	Station 2	0.48	3.85	18.28		0.21	0.28	1.34
TH27-2-2	Station 2	0.62	1.27	4.82		0.16	0.28	1.70
TH27-2-3	Station 2	0.72	1.82	12.63		0.22	0.41	1.90
TH27-2-4	Station 2	0.88	2.34	18.26		0.11	0.26	2.29
TH27-3-2	Station 2	1.53	1.08	2.10				
TH27-4-1	Station 2	2.32	0.98	<D.L.		0.09	0.18	1.94
TH27-4-2	Station 2	2.47	0.83	<D.L.		0.09	0.18	1.92
TH27-4-3	Station 2	2.62	1.13	<D.L.		0.10	0.23	2.34
TH27-4-4	Station 2	2.77	1.17	<D.L.		0.09	0.19	1.96
TH27-4-5	Station 2	2.92	1.14	<D.L.		0.09	0.19	2.17
TH27-4-6	Station 2	3.05	1.07	<D.L.		0.10	0.19	2.03
TH27-5-1	Station 2	3.22	0.91	<D.L.		0.10	0.20	2.06
TH27-5-2	Station 2	3.36	1.24	<D.L.		0.10	0.20	1.95
TH27-5-3	Station 2	3.51	1.30	<D.L.		0.10	0.18	1.79
TH27-6-1	Station 2	4.16	1.36	<D.L.		0.10	0.17	1.71
TH30								
TH30-1-1	Station 3	0.03	3.91	2.10		0.18	0.26	1.48
TH30-1-2	Station 3	0.17	19.65	3.97		0.18	0.26	1.46
TH30-2-1	Station 3	0.37	0.95	1.12		0.21	0.30	1.42
TH30-2-2	Station 3	0.52	0.73	<D.L.		0.25	0.33	1.33

TH30-2-3	Station 3	0.67	0.37	1.20		0.30	0.42	1.38
TH30-2-4	Station 3	0.82	0.30	0.54		0.22	0.30	1.35
TH30-3-1	Station 3	1.24	0.24	<D.L.		0.18	0.32	1.76
TH30-3-2	Station 3	1.40	0.27	<D.L.		0.25	0.33	1.32
TH30-3-3	Station 3	1.55	0.14	<D.L.		0.16	0.32	2.06
TH26								
TH26-1-1	Station 4	0.14	28.40	1.41		0.20	0.25	1.25
TH26-1-2	Station 4	0.29	4.56	7.53		0.18	0.27	1.49
TH26-2-1	Station 4	0.41	3.30	7.32		0.18	0.28	1.53
TH26-2-2	Station 4	0.56	2.50	4.02		0.19	0.35	1.82
TH26-2-3	Station 4	0.71	2.58	2.05		0.19	0.36	1.93
TH26-2-4	Station 4	0.85	0.76	0.65		0.10	0.16	1.59
TH26-3-1	Station 4	1.34	0.91	<D.L.		0.17	0.28	1.70
TH26-3-2	Station 4	1.52	0.84	<D.L.		0.15	0.22	1.50
TH26-3-3	Station 4	1.67	1.01	0.62		0.12	0.23	1.88
TH26-3-4	Station 4	1.84	0.94	<D.L.		0.09	0.19	2.08
TH26-3-5	Station 4	2.02	0.97	2.36		0.10	0.20	2.06
TH26-4-1	Station 4	2.26	0.87	<D.L.		0.12	0.19	1.57
TH26-4-2	Station 4	2.41	1.00	<D.L.		0.11	0.20	1.88
TH26-4-3	Station 4	2.57	0.19	<D.L.		0.07	0.11	1.53
TH26-4-4	Station 4	2.78	2.22	0.71		0.05	0.08	1.56
TH26-4-5	Station 4	2.93	0.67	1.02		0.07	0.11	1.64
TH26-5-1	Station 4	3.15	0.61	0.96		0.06	0.08	1.44
TH26-5-2	Station 4	3.35	0.56	1.50		0.06	0.08	1.44
TH26-5-3	Station 4	3.55	0.61	5.16		0.05	0.07	1.39
TH26-5-4	Station 4	3.75	0.72	9.03		0.05	0.08	1.65
TH26-5-5	Station 4	3.95	0.52	0.85		0.05	0.07	1.37
TH26-6-1	Station 4	4.07	0.55	1.45		0.05	0.07	1.25
TH26-6-2	Station 4	4.32	0.55	3.27		0.05	0.07	1.44
TH26-6-3	Station 4	4.57	0.61	5.54		0.05	0.08	1.51
			0.22					
TH31								
TH31-1-1	Station 5	0.10	9.99	1.29		0.16	0.22	1.35
TH31-1-2	Station 5	0.26	5.87	1.07		0.17	0.26	1.50
TH31-2-1	Station 5	0.33	3.30	0.65		0.18	0.28	1.54
TH31-2-2	Station 5	0.49	2.09	0.96		0.18	0.33	1.88
TH31-2-3	Station 5	0.64	1.33	1.15		0.13	0.22	1.67
TH31-3-1	Station 5	1.28	0.52	1.35		0.17	0.18	1.10
TH31-3-2b	Station 5	1.38	0.22	<D.L.		0.12	0.20	1.58
TH31-3-3	Station 5	1.57	0.73	0.50		0.19	0.26	1.36
TH31-3-4b	Station 5	1.64	0.31	<D.L.		0.17	0.20	1.15
TH31-4-1b	Station 5	2.20	0.36	<D.L.		0.09	0.11	1.12
TH31-4-2	Station 5	2.31	0.59	<D.L.		0.09	0.16	1.70
TH31-4-3b	Station 5	2.50	0.85	<D.L.		0.09	0.14	1.57
TH31-4-4	Station 5	2.61	0.82	<D.L.		0.10	0.18	1.79

TH31-4-5	Station 5	2.76	0.80	<D.L.		0.10	0.19	1.83
TH31-5-1	Station 5	3.10	0.64	<D.L.		0.10	0.11	1.12
TH31-5-2	Station 5	3.25	0.74	<D.L.		0.09	0.11	1.25
TH31-5-3	Station 5	3.45	0.73	<D.L.		0.13	0.20	1.48
TH31-5-4	Station 5	3.67	0.00	<D.L.		0.19	0.25	1.30
TH31-6-1b	Station 5	4.11	0.16	<D.L.		0.10	0.12	1.16
TH31-6-2b	Station 5	4.25	0.15	<D.L.		0.15	0.27	1.82
TH31-6-3	Station 5	4.55	0.10	<D.L.		0.08	0.14	1.78
TH31-7-1	Station 5	4.90	0.00	<D.L.		0.07	0.09	1.36
TH31-7-2	Station 5	5.20	0.29	<D.L.		0.17	0.29	1.73
TH31-7-3	Station 5	5.50	0.37	<D.L.		0.15	0.23	1.56
TH31-7-4	Station 5	5.72	1.35	<D.L.		0.15	0.25	1.65
TH23								
TH23-1-1	Station 6	0.10	22.70	0.44		0.16	0.23	1.46
TH23-1-2	Station 6	0.20	16.12	6.43		0.17	0.35	2.12
TH23-2-1	Station 6	0.43	3.10	0.26		0.11	0.19	1.69
TH23-2-2	Station 6	0.53	1.93	0.29		0.10	0.13	1.33
TH23-2-3	Station 6	0.73	0.34	0.41		0.04	0.06	1.75
TH23-3-1	Station 6	1.28	0.16	0.45		0.05	0.05	1.02
TH23-3-2	Station 6	1.43	0.25	1.80		0.05	0.04	0.94
TH23-3-3	Station 6	1.57	0.19	<D.L.		0.03	0.04	1.15
TH23-3-4	Station 6	1.74	0.00	<D.L.		0.09	0.17	1.81
TH23-3-5	Station 6	1.89	0.09	<D.L.		0.06	0.12	1.98
TH23-4-1	Station 6	2.19	0.12	<D.L.		0.06	0.08	1.23
TH23-4-2	Station 6	2.33	0.00	<D.L.		0.06	0.08	1.40
TH23-4-3	Station 6	2.47	0.00	<D.L.		0.04	0.06	1.59
TH23-5-1	Station 6	3.13	0.72	<D.L.		0.02	0.02	0.82
TH23-5-2	Station 6	3.37	3.60	7.56		0.03	0.07	2.09
TH23-6-1	Station 6	4.14	2.32	7.10		0.04	0.02	0.62
TH25								
TH25-1-1	Station 7	0.03	<D.L.	<D.L.		0.08	0.08	0.97
TH25-1-2	Station 7	0.18	13.58	<D.L.		0.24	0.39	1.59
TH25-2-1	Station 7	0.33	5.77	<D.L.		0.20	0.17	0.85
TH25-2-2	Station 7	0.49	3.79	<D.L.		0.08	0.10	1.26
TH25-2-3	Station 7	0.65	0.65	<D.L.		0.09	0.18	1.92
TH25-2-4	Station 7	0.80	0.49	<D.L.		0.10	0.16	1.64
TH25-3-1	Station 7	1.29	0.50	<D.L.		0.11	0.18	1.67
TH25-3-2	Station 7	1.45	0.33	1.35		0.05	0.09	1.79
TH25-3-3	Station 7	1.60	0.42	<D.L.		0.05	0.09	1.78
TH25-3-4	Station 7	1.75	0.48	<D.L.		0.06	0.11	1.84
TH25-3-5	Station 7	1.90	1.10	0.18		0.06	0.07	1.21
TH25-4-1	Station 7	2.23	0.33	<D.L.		0.07	0.11	1.43
TH25-4-2	Station 7	2.38	0.26	<D.L.		0.07	0.10	1.40
TH25-4-3	Station 7	2.53	0.23	<D.L.		0.07	0.10	1.40

TH25-4-4	Station 7	2.68	0.22	<D.L.		0.07	0.12	1.62
TH25-4-5	Station 7	2.83	0.31	<D.L.		0.07	0.11	1.56
TH25-5-1	Station 7	3.11	0.38	<D.L.		0.07	0.08	1.22
TH25-5-2	Station 7	3.31	0.25	<D.L.		0.07	0.10	1.45
TH25-5-3	Station 7	3.52	0.27	<D.L.		0.07	0.12	1.63
TH25-5-4	Station 7	3.72	0.32	<D.L.		0.09	0.15	1.60
TH25-6-1	Station 7	4.06	0.53	<D.L.		0.17	0.33	1.88
TH25-6-2	Station 7	4.31	0.30	<D.L.		0.08	0.17	2.18
TH25-6-3	Station 7	4.56	0.35	<D.L.		0.07	0.13	1.84
TH25-7-1	Station 7	4.98	0.45	<D.L.		0.10	0.14	1.48
TH25-7-2	Station 7	5.28	0.00	<D.L.		0.11	0.22	2.06
TH25-7-3	Station 7	5.56	0.47	<D.L.		0.13	0.20	1.60
			0.38					
TH24								
TH24-1-1	Station 8	0.06	29.61	9.82		0.22	0.28	1.31
TH24-1-2	Station 8	0.20	23.32	6.25		0.24	0.36	1.51
TH24-2-1	Station 8	0.37	7.53	<D.L.		0.18	0.31	1.69
TH24-2-2	Station 8	0.51	1.49	<D.L.		0.12	0.29	2.45
TH24-2-3	Station 8	0.65	1.55	<D.L.		0.13	0.23	1.85
TH24-3-1	Station 8	1.39	2.80	18.43		0.10	0.25	2.52
TH24-3-2	Station 8	1.53	3.12	15.63		0.10	0.21	2.18
TH24-3-3	Station 8	1.70	6.73	11.48		0.09	0.17	1.82
TH24-4-1	Station 8	2.20	5.66	<D.L.		0.10	0.23	2.35
TH24-4-2	Station 8	2.37	7.55	<D.L.		0.10	0.21	2.10
TH24-4-3	Station 8	2.55	7.79	<D.L.		0.10	0.18	1.84
TH24-4-4	Station 8	2.70	7.67	<D.L.		0.11	0.22	2.02
TH24-4-5	Station 8	2.87	7.12	<D.L.		0.10	0.20	1.94
TH24-4-6	Station 8	3.01	6.90	<D.L.		0.07	0.16	2.23
TH24-5-1	Station 8	3.13	6.63	<D.L.		0.09	0.14	1.54
TH24-5-2	Station 8	3.29	7.08	<D.L.		0.10	0.20	1.96
TH24-5-3	Station 8	3.50	4.04	<D.L.		0.04	0.07	1.60
TH24-6-1	Station 8	4.04	3.87	5.90		0.05	0.04	0.91
TH24-6-2	Station 8	4.40	2.40	<D.L.		0.05	0.10	1.95
DECEMBER 2007								
TH 32								
TH32-1-1	Station 9	0.06	2.75			0.33	0.42	1.30
TH32-1-2	Station 9	0.21	2.09			0.27	0.42	1.54
TH32-1-3	Station 9	0.35	0.49			0.12	0.16	1.28
TH32-2-1	Station 9	0.43	0.82			0.04	0.05	1.24
TH32-2-2	Station 9	0.58	1.66			0.02	0.03	1.50
TH32-2-3	Station 9	0.83	0.21			0.05	0.10	2.03
TH32-2-4	Station 9	0.99	0.15			0.03	0.04	1.42
TH32-3-1	Station 9	1.46	0.25			0.09	0.10	1.15
TH32-3-2	Station 9	1.62	0.19			0.12	0.25	2.01
TH32-3-3	Station 9	1.77	0.22			0.14	0.28	2.02

TH32-3-4	Station 9	1.92	0.18			0.08	0.16	2.07
TH32-3-5	Station 9	2.09	0.18			0.07	0.13	1.80
TH32-4-1	Station 9	2.70	0.22			0.05	0.05	0.96
TH32-4-2	Station 9	2.85	0.14			0.04	0.05	1.40
TH32-4-3	Station 9	3.00	0.12			0.03	0.05	1.64
TH32-5-1	Station 9	3.82	0.45			0.08	0.16	2.00
TH32-5-2	Station 9	3.97	0.58			0.04	0.09	2.28
TH32-6-1	Station 9	4.80	0.50			0.10	0.22	2.27
TH 33								
TH33-1-1	Station 10	0.05	0.03			0.19	0.30	1.54
TH33-1-2	Station 10	0.20	1.15			0.22	0.31	1.44
TH33-2-1	Station 10	0.34	0.16			0.20	0.31	1.55
TH33-2-2	Station 10	0.52	0.39			0.07	0.11	1.46
TH33-2-3	Station 10	0.66	0.09			0.03	0.05	1.67
TH33-2-4	Station 10	0.81	0.09			0.02	0.03	1.68
TH33-2-5	Station 10	0.96	0.14			0.03	0.05	1.69
TH33-2-6	Station 10	1.12	0.15			0.02	0.02	1.03
TH33-3-1	Station 10	1.26	0.39			0.02	0.03	1.32
TH33-3-2	Station 10	1.41	0.07			0.02	0.04	1.64
TH33-3-3	Station 10	1.56	0.04			0.02	0.04	1.67
TH33-3-4	Station 10	1.71	0.02			0.02	0.03	1.60
TH33-3-5	Station 10	1.86	0.04			0.02	0.04	1.67
TH33-3-6	Station 10	2.01	0.50			0.02	0.03	1.35
TH33-4-1	Station 10	2.16	0.07			0.03	0.04	1.51
TH33-4-2	Station 10	2.31	0.30			0.03	0.04	1.63
TH33-4-3	Station 10	2.46	0.14			0.03	0.05	1.66
TH33-4-4	Station 10	2.61	0.09			0.03	0.05	1.64
TH33-4-5	Station 10	2.76	0.09			0.04	0.06	1.65
TH33-4-6	Station 10	2.91	0.17			0.05	0.08	1.59
TH33-5-1	Station 10	3.10	0.21			0.07	0.09	1.33
TH33-5-2	Station 10	3.25	0.69			0.10	0.15	1.45
TH33-5-3	Station 10	3.40	0.83			0.17	0.27	1.61
TH33-5-4	Station 10	3.55	0.94			0.19	0.28	1.46
TH33-5-5	Station 10	3.70	0.88			0.15	0.23	1.52
TH33-5-6	Station 10	3.85	0.38			0.06	0.09	1.45
TH33-6-1	Station 10	4.00	0.14			0.07	0.05	0.78
TH33-6-2	Station 10	4.17	0.53			0.05	0.05	1.11
TH33-6-3	Station 10	4.32	0.20			0.03	0.04	1.26
TH33-6-4	Station 10	4.47	0.20			0.03	0.04	1.38
TH 34								
TH34-1-1	Station 11	0.03	0.78			0.31	0.41	1.33
TH34-1-2	Station 11	0.18	3.57			0.35	0.49	1.39
TH34-1-3	Station 11	0.33	2.79			0.22	0.38	1.70
TH34-2-1	Station 11	0.44	0.86			0.11	0.17	1.52

TH34-2-2	Station 11	0.62	0.86			0.08	0.10	1.21
TH34-2-3	Station 11	1.06	0.77			0.09	0.16	1.91
TH34-2-4	Station 11	1.23	0.79			0.08	0.17	2.03
TH34-3-1	Station 11	1.45	0.20			0.09	0.18	1.98
TH34-3-2	Station 11	1.59	0.24			0.09	0.19	2.13
TH34-3-3	Station 11	1.74	0.90			0.09	0.16	1.91
TH34-3-4	Station 11	1.93	0.43			0.08	0.16	1.88
TH34-3-5	Station 11	2.11	0.37			0.09	0.16	1.73
TH34-4-1	Station 11	2.37	0.67			0.09	0.19	2.02
TH34-4-2	Station 11	2.52	0.79			0.10	0.18	1.83
TH34-4-3	Station 11	2.67	0.85			0.10	0.20	1.98
TH34-4-4	Station 11	2.84	0.98			0.10	0.18	1.80
TH34-4-5	Station 11	2.98	1.14			0.11	0.18	1.69
TH34-5-1	Station 11	3.14	0.63			0.11	0.22	1.95
TH34-5-2	Station 11	3.30	1.23			0.10	0.19	1.89
TH34-5-3	Station 11	3.47	1.80			0.11	0.20	1.84
TH34-5-4	Station 11	3.61	2.09			0.11	0.21	1.91
TH34-5-5	Station 11	3.76	1.48			0.10	0.19	1.95
TH34-5-6	Station 11	3.91	0.49			0.08	0.14	1.86
TH34-6-1	Station 11	4.07	0.46			0.08	0.16	1.99
TH34-6-2	Station 11	4.20	0.33			0.10	0.18	1.75
TH34-6-3	Station 11	4.36	0.21			0.10	0.18	1.77
TH34-6-4	Station 11	4.54	0.26			0.10	0.16	1.59
TH34-6-5	Station 11	4.74	0.31			0.10	0.17	1.74
TH34-6-6	Station 11	4.92	0.29			0.08	0.14	1.72
TH34-7-1	Station 11	4.97	0.29			0.09	0.21	2.25
TH34-7-2	Station 11	5.11	0.24			0.10	0.19	1.88
TH34-7-3	Station 11	5.26	0.30			0.09	0.20	2.16
TH34-7-4	Station 11	5.41	0.40			0.10	0.20	2.11
TH34-7-5	Station 11	5.55	0.28			0.09	0.21	2.29
TH34-7-6	Station 11	5.70	0.64			0.10	0.20	2.06
TH34-8-1	Station 11	5.89	0.23			0.10	0.21	2.07
TH34-8-2	Station 11	6.04	0.23			0.10	0.19	1.87
TH34-8-3	Station 11	6.18	0.28			0.10	0.18	1.69
TH34-8-4	Station 11	6.34	0.21			0.10	0.20	1.94
TH34-8-5	Station 11	6.50	0.46			0.11	0.21	1.98
TH34-8-6	Station 11	6.65	0.26			0.10	0.20	2.06
TH 35								
TH35-1-1	Station 12	0.12	8.03			0.30	0.38	1.28
TH35-1-2	Station 12	0.27	1.52			0.25	0.40	1.60
TH35-2-1	Station 12	0.33	0.80			0.20	0.27	1.34
TH35-2-2	Station 12	0.98	1.73			0.14	0.27	1.86
TH35-2-3	Station 12	1.11	0.75			0.06	0.11	1.75
TH35-3-1	Station 12	1.29	0.41			0.03	0.04	1.37
TH35-3-2	Station 12	1.47	0.18			0.04	0.04	1.11
TH35-3-3	Station 12	1.70	0.19			0.02	0.04	1.74

TH35-4-1	Station 12	2.82	0.09			0.07	0.09	1.30
TH35-4-2	Station 12	2.97	0.04			0.08	0.07	0.85
TH 36								
TH36-1-1	Station 13	0.08	10.01			0.26	0.37	1.41
TH36-1-2	Station 13	0.23	0.36			0.26	0.35	1.35
TH36-1-3	Station 13	0.38	0.88			0.24	0.38	1.58
TH36-2-1	Station 13	1.24	1.17			0.09	0.13	1.50
TH36-2-2	Station 13	1.39	1.03			0.06	0.10	1.55
TH36-2-3	Station 13	1.56	0.86			0.05	0.09	1.73
TH36-2-4	Station 13	1.72	0.89			0.04	0.08	1.84
TH36-3-1	Station 13	2.21	0.16			0.03	0.05	1.72
TH36-3-2	Station 13	2.36	0.19			0.03	0.05	1.66
TH36-3-3	Station 13	2.51	0.17			0.03	0.05	1.54
TH 37								
TH37-1-1	Station 14	0.06	30.01			0.13	0.13	1.02
TH37-1-2	Station 14	0.21	13.57			0.16	0.23	1.47
TH37-2-1	Station 14	0.89	4.61			0.29	0.28	0.97
TH37-2-2	Station 14	1.04	1.41			0.18	0.31	1.71
TH37-2-3	Station 14	1.19	1.13			0.12	0.13	1.07
TH37-3-1	Station 14	1.24	1.29			0.10	0.10	1.01
TH37-3-2	Station 14	1.39	1.09			0.07	0.10	1.34
TH37-3-3	Station 14	1.54	1.94			0.06	0.09	1.41
TH37-3-4	Station 14	1.69	1.57			0.04	0.05	1.05
TH37-4-1	Station 14	2.16	1.96			0.06	0.09	1.59
TH37-4-2	Station 14	2.31	0.14			0.07	0.11	1.58
TH37-4-3	Station 14	2.46	0.82			0.07	0.10	1.58
TH37-4-4	Station 14	2.61	0.25			0.08	0.12	1.60
TH37-5-1	Station 14	3.07	0.14			0.06	0.08	1.37
TH37-5-2	Station 14	3.22	0.38			0.06	0.09	1.35
TH37-5-3	Station 14	3.37	0.58			0.07	0.09	1.32
TH37-5-4	Station 14	3.52	0.62			0.07	0.09	1.35
TH37-6-1	Station 14	3.99	0.59			0.07	0.11	1.60
TH37-6-2	Station 14	4.14	0.50			0.06	0.08	1.48
TH37-6-3	Station 14	4.29	0.30			0.06	0.09	1.54
TH37-6-4	Station 14	4.44	0.30			0.06	0.10	1.56
TH37-7-1	Station 14	4.90	0.99			0.07	0.09	1.30
TH37-7-2	Station 14	5.05	1.30			0.06	0.08	1.46
TH37-7-3	Station 14	5.20	1.08			0.05	0.08	1.56
TH37-7-4	Station 14	5.35	0.93			0.05	0.07	1.28
TH37-7-5	Station 14	5.50	1.30			0.05	0.07	1.36
TH37-8-1	Station 14	5.82	0.73			0.09	0.11	1.25
TH37-8-2	Station 14	5.97	0.66			0.07	0.10	1.41
TH37-8-3	Station 14	6.12	0.50			0.07	0.09	1.31
TH37-8-4	Station 14	6.27	1.86			0.07	0.11	1.44

TH37-9-1	Station 14	6.73	0.63			0.12	0.22	1.81
TH37-9-2	Station 14	6.88	0.98			0.06	0.09	1.50
TH37-9-3	Station 14	7.03	2.86			0.13	0.19	1.46
TH37-9-4	Station 14	7.18	1.43			0.07	0.11	1.43
TH37-9-5	Station 14	7.33	0.89			0.06	0.09	1.41
TH37-10-1	Station 14	7.65	2.21			0.08	0.13	1.55
TH37-10-2	Station 14	7.80	2.45			0.07	0.11	1.64
TH37-10-3	Station 14	7.95	3.57			0.09	0.15	1.71
TH37-10-4	Station 14	8.10	3.20			0.08	0.13	1.67
TH37-10-5	Station 14	8.25	4.41			0.11	0.19	1.69
TH37-11-2	Station 14	8.71	6.27			0.13	0.23	1.67
TH37-11-3	Station 14	8.86	4.59			0.10	0.16	1.62
TH37-11-4	Station 14	9.01	4.34			0.08	0.13	1.65
TH37-11-5	Station 14	9.16	5.84			0.14	0.25	1.85
TH37-11-6	Station 14	9.31	2.81			0.15	0.28	1.89
TH 38								
TH38-1-1	Station 15	0.05	3.10			0.28	0.38	1.35
TH38-1-2	Station 15	0.21	2.19			0.22	0.33	1.47
TH38-2-1	Station 15	0.65	2.15			0.30	0.33	1.10
TH38-2-2	Station 15	0.80	5.59			0.19	0.27	1.42
TH38-2-3	Station 15	0.95	0.86			0.15	0.26	1.70
TH38-2-4	Station 15	1.10	0.47			0.17	0.24	1.44
TH38-3-1	Station 15	1.24	0.59			0.10	0.14	1.47
TH38-3-2	Station 15	1.39	0.78			0.04	0.07	1.53
TH38-3-3	Station 15	1.54	0.57			0.03	0.05	1.50
TH38-3-4	Station 15	1.69	0.32			0.03	0.04	1.50
TH38-3-5	Station 15	1.84	0.33			0.03	0.04	1.28
TH38-4-1	Station 15	2.20	0.28			0.03	0.04	1.18
TH38-4-2	Station 15	2.35	0.37			0.04	0.06	1.51
TH38-4-3	Station 15	2.49	0.29			0.06	0.10	1.75
TH38-4-4	Station 15	2.64	0.75			0.09	0.15	1.61
TH38-4-5	Station 15	2.79	0.58			0.03	0.04	1.22
TH38-5-1	Station 15	3.07	0.29			0.04	0.06	1.38
TH38-5-2	Station 15	3.22	0.36			0.05	0.07	1.44
TH38-5-3	Station 15	3.37	0.47			0.06	0.08	1.38
TH38-5-4	Station 15	3.52	0.45			0.07	0.10	1.48
TH38-6-1	Station 15	4.25	0.56			0.06	0.07	1.12
TH38-6-2	Station 15	4.42	0.58			0.07	0.10	1.36
TH38-6-3	Station 15	4.57	0.69			0.06	0.09	1.49
TH38-6-4	Station 15	4.72	0.65			0.07	0.10	1.48
TH38-7-1	Station 15	4.99	1.65			0.05	0.06	1.13
TH38-7-2	Station 15	5.14	0.68			0.06	0.10	1.76
TH38-7-3	Station 15	5.28	0.64			0.06	0.10	1.60
TH38-7-4	Station 15	5.43	0.67			0.05	0.06	1.27
TH38-7-5	Station 15	5.58	0.65			0.05	0.07	1.42

TH38-7-6	Station 15	5.73	0.55			0.05	0.04	0.97
MAY 2008								
TH50A-1-1	Station 1	0.09	0.16	0.75	0.28	0.33	0.33	0.99
TH50A-1-2	Station 1	0.24	4.24	8.02	10.41	0.26	0.25	0.95
TH50A-2-1	Station 1	0.33	0.00	1.51	12.32	0.17	0.27	1.60
TH50A-2-2	Station 1	0.48	0.11	1.71	13.19	0.07	0.12	1.93
TH50A-2-3	Station 1	0.64	0.19	2.60	30.78	0.05	0.08	2.38
TH50A-2-4	Station 1	0.79	0.44	2.27	22.05	0.03	0.05	1.72
TH50A-3-1	Station 1	1.29	0.43	1.51	54.04	0.04	0.06	1.46
TH50A-3-2	Station 1	1.44	0.38	1.71	28.69	0.04	0.06	2.27
TH50A-3-3	Station 1	1.69	0.68	1.38	37.51	0.04	0.09	2.08
TH50A-3-4	Station 1	1.84	0.26	1.02	29.87	0.05	0.10	1.86
TH50A-4-1	Station 1	2.21	0.37	1.69	29.26	0.07	0.12	1.57
TH50A-5-1	Station 1	3.12	1.08	1.98	29.68	0.08	0.14	1.71
TH50A-5-2	Station 1	3.27	0.59	1.03	25.02	0.08	0.17	2.04
TH50A-5-3	Station 1	3.43	0.77	0.98	22.55	0.08	0.13	1.57
TH45-1-1	Station 2	0.08	7.43	51.19	3.64	0.22	0.33	1.49
TH45-1-2	Station 2	0.23	9.27	113.30	2.27	0.23	0.31	1.37
TH45-2-1	Station 2	0.34	2.09	54.07	3.28	0.29	0.43	1.48
TH45-2-2	Station 2	0.49	2.13	29.46	1.96		0.98	0.90
TH45-2-3	Station 2	0.98	1.45	19.49	1.90	0.17	0.29	1.76
TH45-2-4	Station 2	1.13	0.92	5.19	2.38	0.11	0.22	2.04
TH45-3-1	Station 2	1.30	0.73	2.35	1.80	0.10	0.21	2.06
TH45-3-2	Station 2	1.45	0.96	1.50	1.58	0.10	0.20	2.05
TH45-3-3	Station 2	1.64	1.00	0.00	1.68	0.11	0.21	2.00
TH45-3-4	Station 2	1.79	1.10	0.00	5.05	0.09	0.20	2.20
TH45-3-5	Station 2	1.94	1.02	0.00	1.26	0.09	0.19	2.09
TH45-4-1	Station 2	2.21	1.11	1.36	2.38	0.10	0.21	2.06
TH45-4-2	Station 2	2.41	1.53	1.22	2.52	0.11	0.22	2.01
TH45-4-3	Station 2	2.56	1.33	0.00	2.88	0.09	0.21	2.24
TH45-4-4	Station 2	2.71	1.28	0.00	2.82	0.10	0.23	2.25
TH45-4-5	Station 2	2.86	1.44	0.00	2.56	0.11	0.23	2.11
TH45-4-6	Station 2	3.01	1.36	0.00	3.10	0.10	0.22	2.11
TH45-6-1	Station 2	4.03	0.94	1.32	4.72	0.11	0.23	2.03
TH52-1-1	Station 3	0.03	8.74	7.36	9.19	0.24	0.32	1.33
TH52-1-2	Station 3	0.18	8.88	2.85	3.72	0.21	0.30	1.43
TH52-2-1	Station 3	0.33	0.92	2.72	2.75	0.22	0.37	1.71
TH52-2-2	Station 3	0.48	2.49	1.97	6.62	0.22	0.34	1.52
TH52-2-3	Station 3	0.63	0.71	5.48	3.51	0.21	0.32	1.53
TH52-3-1	Station 3	1.31	0.33	6.32	4.67	0.09	0.13	1.50
TH52-3-2	Station 3	1.45	0.52	3.48	12.34	0.07	0.10	1.47
TH52-3-3	Station 3	1.60	0.07	4.04	6.30	0.09	0.10	1.22
Th52-4-1	Station 3	2.16	0.41	4.64	7.13	0.09	0.16	1.77

TH52-4-2	Station 3	2.31	0.17	3.02	11.23	0.08	0.15	1.87
Th52-4-3	Station 3	2.49	0.65	1.34	10.42	0.08	0.15	1.85
TH52-5-1	Station 3	3.12	0.24	1.04	17.21	0.05	0.08	1.55
TH52-5-2	Station 3	3.27	0.11	1.35	29.00	0.06	0.07	1.19
TH39-1-1	Station 4	0.06	7.65	4.01	38.42	0.21	0.33	1.59
TH39-1-2	Station 4	0.21	12.21	47.08	20.55	0.22	0.32	1.47
TH39-2-1	Station 4	0.33	2.67	77.00	6.99	0.22	0.35	1.62
TH39-2-2	Station 4	0.48	2.99	797.61	5.26	0.20	0.32	1.55
TH39-2-3	Station 4	0.63	2.34	49.91	3.28	0.20	0.34	1.68
TH39-2-4	Station 4	0.78	0.84	10.54	0.95	0.13	0.23	1.78
TH39-3-1	Station 4	1.29	1.31	42.63	1.54	0.18	0.32	1.71
TH39-3-2	Station 4	1.44	1.17	10.93	1.46	0.19	0.32	1.68
TH39-3-3	Station 4	1.60	0.80	7.42	1.46	0.14	0.26	1.86
TH39-3-4	Station 4	1.75	0.99	9.68	2.52	0.11	0.22	2.04
TH39-4-1	Station 4	2.31	1.21	1.93	3.64	0.09	0.21	2.31
TH39-4-2	Station 4	2.46	1.21	2.14	3.45	0.11	0.24	2.21
TH39-4-3	Station 4	2.61	0.52	2.47	8.84	0.05	0.08	1.75
TH39-4-4	Station 4	2.76	0.40	1.62	8.99	0.04	0.07	1.61
TH39-4-5	Station 4	2.91	0.34	1.55	9.82	0.04	0.07	1.63
TH39-5-1	Station 4	3.12	0.36	1.75	5.57	0.05	0.07	1.35
TH39-5-2	Station 4	3.27	0.57	1.02	6.70	0.05	0.07	1.48
TH39-5-3	Station 4	3.42	0.50	1.27	7.01	0.05	0.08	1.46
TH39-5-4	Station 4	3.57	0.72	1.68	8.39	0.05	0.07	1.39
TH39-5-5	Station 4	3.72	0.53	2.03	7.47	0.05	0.07	1.51
TH39-6-1	Station 4	3.99	0.84	3.36	10.10	0.07	0.10	1.45
TH39-6-2	Station 4	4.14	0.62	2.72	3.33	0.05	0.08	1.47
TH39-6-3	Station 4	4.29	0.86	3.09	4.24	0.05	0.08	1.41
TH39-6-4	Station 4	4.44	0.61	2.76	4.28	0.05	0.08	1.44
TH39-6-5	Station 4	4.59	0.75	3.04	4.31	0.06	0.09	1.37
TH49-1-1	Station 6	0.13	16.13	22.48	5.25	0.16	0.43	2.63
TH49-2-1	Station 6	0.34	0.14	97.65	9.19	0.06	0.09	1.51
TH49-2-2	Station 6	0.50	0.39	149.65	27.52	0.05	0.05	1.05
TH49-2-3	Station 6	0.66	0.08	320.20	23.47	0.03	0.05	1.66
TH49-2-4	Station 6	0.82	0.22	202.88	31.72	0.04	0.06	1.35
TH49-3-1	Station 6	1.24	0.15	91.79	11.58	0.05	0.08	1.71
TH49-3-2	Station 6	1.39	0.20	23.88	6.03	0.06	0.04	1.59
TH49-3-3	Station 6	1.54	0.60	15.45	10.23	0.08	0.05	1.51
TH49-3-4	Station 6	1.69	0.86	1.81	8.02	0.10	0.05	1.68
TH49-3-5	Station 6	1.84	0.34	1.02	6.47	0.01	0.06	1.54
TH49-4-1	Station 6	2.16	0.68	1.42	7.62	0.06	0.08	1.43
TH49-4-2	Station 6	2.31	0.31	1.04	4.65	0.08	0.13	1.61
TH49-4-3	Station 6	2.47	0.26	0.67	10.00	0.03	0.06	1.90
TH49-4-4	Station 6	2.63	1.06	1.84	23.23	0.03	0.05	1.64
TH49-5-1	Station 6	3.07	1.11	1.83	13.17	0.04	0.04	1.25

TH49-5-2	Station 6	3.22	1.74	2.27	30.85	0.03	0.04	1.35
TH49-5-3	Station 6	3.37	1.74	2.46	57.33	0.03	0.04	1.40
TH49-5-4	Station 6	3.52	1.76	0.61	29.61	0.04	0.04	1.27
TH47b-1-1	Station 8	0.08	7.76	5.46	70.94	0.23	0.30	1.33
TH47b-1-2	Station 8	0.23	6.89	1.39	4.13	0.21	0.32	1.53
TH47b-2-1	Station 8	0.33	1.70	1.29	1.70	0.26	0.42	1.60
TH47b-2-2	Station 8	0.48	0.74	0.00	1.33	0.09	0.16	1.69
TH47b-2-3	Station 8	0.63	0.99	0.00	1.28	0.09	0.15	1.63
TH47b-3-1	Station 8	1.24	0.88	2.10	21.03	0.08	0.11	1.45
TH47b-3-2	Station 8	1.39	0.72	0.97	7.36	0.09	0.12	0.64
TH47b-3-3	Station 8	1.54	1.62	2.87	4.90	0.09	0.18	0.95
TH47b-5-1	Station 8	2.19	2.88	10.16	4.85	0.10	0.19	1.89
TH47b-4-1	Station 8	3.07	2.69	12.72	14.35	0.09	0.15	1.63
TH47b-4-2	Station 8	3.21	3.07	6.45	20.90	0.10	0.20	1.98
TH47b-4-3	Station 8	3.45	2.17	4.20	20.07	0.05	0.06	1.34
TH47b-4-4	Station 8	3.60	1.77	1.16	16.96	0.04	0.06	1.28
TH48a-1-1	Station 9	0.03	1.78	12.32	11.16	0.28	0.29	1.03
TH48a-1-2	Station 9	0.18	13.43	3.25	9.19	0.24	0.29	1.22
TH48a-1-3	Station 9	0.32	0.76	5.15	8.45	0.20	0.26	1.31
TH48a-2-1	Station 9	0.33	1.63	8.15	6.54	0.15	0.27	1.76
TH48a-2-2	Station 9	0.48	0.26	2.32	8.50	0.07	0.12	1.78
TH48a-2-3	Station 9	0.64	0.14	16.20	7.10	0.05	0.10	1.97
TH48-3-1	Station 9	1.34	0.33	28.70	6.68	0.09	0.18	2.01
TH48-3-2	Station 9	1.52	0.22	13.80	13.09	0.05	0.08	1.53
TH48a-4-1	Station 9	2.27	0.28	20.06	14.71	0.09	0.17	1.86
TH48a-4-2	Station 9	2.42	0.46	1.41	14.44	0.10	0.24	2.35
TH48a-4-3	Station 9	2.57	0.56	0.65	9.23	0.13	0.22	1.63
TH48a-5-1	Station 9	3.07	1.11	0.76	22.56	0.10	0.16	1.71
TH42-1-1	Station 10	0.08	3.21	13.80	1.36	0.17	0.27	1.54
TH42-1-2	Station 10	0.23	0.00	82.26	1.41	0.10	0.14	1.41
TH42-2-1	Station 10	0.38	1.63	269.19	2.09	0.20	0.32	1.63
TH42-2-2	Station 10	0.53	0.88	113.60	2.87	0.11	0.19	1.81
TH42-2-3	Station 10	0.68	0.64	54.35	5.85	0.30	0.45	1.51
TH42-3-1	Station 10	1.34	0.00	22.59	2.78	0.05	0.08	1.58
TH42-3-2	Station 10	1.49	0.11	22.45	3.91	0.04	0.06	1.51
TH42-3-3	Station 10	1.64	0.11	44.38	4.19	0.04	0.06	1.51
TH42-3-4	Station 10	1.79	0.12	13.90	6.74	0.04	0.07	1.77
TH42-3-5	Station 10	1.94	0.06	3.21	7.96	0.04	0.07	1.55
TH42-4-1	Station 10	2.21	0.09	2.58	5.77	0.03	0.05	1.43
TH42-4-2	Station 10	2.36	0.10	2.20	8.61	0.04	0.06	1.52
TH42-4-3	Station 10	2.51	0.14	3.22	9.81	0.05	0.07	1.59
TH42-4-4	Station 10	2.66	0.29	2.68	8.32	0.06	0.09	1.50
TH42-4-5	Station 10	2.81	0.15	4.82	6.86	0.07	0.11	1.48

TH42-4-6	Station 10	2.96	0.17	12.86	6.76	0.11	0.17	1.65
TH42-5-1	Station 10	3.12	0.17	58.57	11.42	0.19	0.28	1.47
TH42-5-2	Station 10	3.27	0.27	26.30	6.42	0.19	0.30	1.56
TH42-5-3	Station 10	3.42	0.23	7.18	4.78	0.18	0.30	1.63
TH42-5-4	Station 10	3.57	0.63	23.78	3.05	0.20	0.32	1.64
TH42-5-5	Station 10	3.72	0.82	18.66	4.36	0.18	0.29	1.60
TH51-1-1	Station 11	0.10	6.15	100.81	5.41	0.23	0.37	1.58
TH51-1-2	Station 11	0.25	2.35	81.07	4.58	0.22	0.29	1.33
TH51-2-1	Station 11	0.33	1.29	54.84	7.18	0.14	0.25	1.81
TH51-2-2	Station 11	0.48	0.79	37.37	5.91	0.11	0.20	1.87
TH51-2-3	Station 11	0.63	0.79	17.55	9.65	0.11	0.16	0.74
TH51-2-4	Station 11	0.85	0.65	1.00	5.33	0.11	0.15	1.43
TH51-3-1	Station 11	1.24	0.70	0.69	4.35	0.10	0.22	2.19
TH51-3-2	Station 11	1.39	0.49	0.00	5.21	0.09	0.20	2.15
TH51-3-3	Station 11	1.89	0.51	0.00	2.96	0.09	0.17	1.78
TH51-3-4	Station 11	2.04	0.51	0.00	2.80	0.09	0.19	1.96
TH51-4-1	Station 11	2.19	1.02	0.00	2.67	0.10	0.21	2.05
TH51-4-2	Station 11	2.34	2.05	0.00	3.21	0.10	0.20	1.98
TH51-4-3	Station 11	2.49	3.23	0.00	3.22	0.10	0.19	0.95
TH51-4-4	Station 11	2.64	4.32	0.00	6.40	0.10	0.20	1.00
TH51-4-5	Station 11	2.79	3.93	0.00	4.52	0.10	0.21	1.00
TH51-4-6	Station 11	2.98	3.80	0.97	9.54	0.11	0.21	1.93
TH51-5-1	Station 11	3.10	2.39	0.57	2.83	0.11	0.21	1.00
TH51-5-2	Station 11	3.24	2.74	0.00	10.03	0.08	0.19	2.40
TH51-5-3	Station 11	3.37	2.84	0.00	3.45	0.11	0.24	2.19
TH51-5-4	Station 11	3.52	3.23	0.69	7.50	0.11	0.22	2.08
TH51-6-1	Station 11	4.00	0.20	1.40	4.58	0.11	0.20	1.79
TH41a-1-1	Station 12	0.08	5.41	178.92	2.70	0.19	0.27	1.41
TH41a-1-2	Station 12	0.23	0.48	394.30	2.45	0.13	0.19	1.50
TH41a-2-1	Station 12	0.38	1.15	66.02	5.87	0.08	0.14	1.69
TH41a-2-2	Station 12	0.53	4.58	149.22	4.10	0.13	0.22	1.68
TH41a-2-3	Station 12	0.68	3.06	341.72	6.62	0.17	0.24	1.41
TH41a-3-1	Station 12	1.31	0.95	23.28	15.68	0.04	0.07	1.54
TH41a-3-2	Station 12	1.71	0.28	32.84	17.86	0.04	0.08	1.84
TH41c-3-1	Station 12	3.32	0.35	1.89	14.15	0.06	0.07	1.22
TH41c-3-2	Station 12	3.47	0.63	4.11	14.51	0.06	0.08	1.46
TH41c-3-3	Station 12	3.68	0.33	9.28	20.66	0.06	0.07	1.24
TH41c-4-1	Station 12	4.04	0.10	12.20	9.10	0.06	0.09	1.49
TH41c-4-2	Station 12	4.19	0.29	11.49	13.28	0.07	0.10	1.51
TH41c-4-3	Station 12	4.34	0.65	8.16	7.52	0.07	0.11	1.51
TH41c-4-4	Station 12	4.49	0.64	6.06	5.28	0.07	0.11	1.54
TH41c-4-5	Station 12	4.64	0.53	1.65	6.01	0.07	0.10	1.52
TH41c-5-1	Station 12	4.95	0.13	0.00	5.96	0.07	0.12	1.69
TH41c-5-2	Station 12	5.10	0.33	0.00	7.34	0.08	0.13	1.68

TH41c-5-3	Station 12	5.25	0.34	0.00	7.73	0.06	0.10	1.56
TH41c-5-4	Station 12	5.40	0.38	0.00	7.96	0.06	0.10	1.72
TH41c-5-5	Station 12	5.55	0.21	0.00	7.73	0.05	0.08	1.61
TH40-1-1	Station 13	0.09	22.27	8.12	7.16	0.24	0.26	1.07
TH40-1-2	Station 13	0.24	3.55	5.90	1.32	0.22	0.28	1.28
TH40-2-1	Station 13	0.38	0.57	29.38	2.07	0.17	0.29	1.64
TH40-2-2	Station 13	0.53	0.52	55.00	1.30	0.19	0.30	1.58
TH40-2-3	Station 13	0.68	0.52	35.41	1.62	0.16	0.25	1.61
TH40-2-4	Station 13	0.83	0.30	77.65	2.70	0.09	0.13	1.50
TH40-3-1	Station 13	1.29	0.45	40.89	2.06	0.08	0.09	1.06
TH40-3-2	Station 13	1.44	0.33	21.40	2.82	0.07	0.09	1.32
TH40-3-3	Station 13	1.59	0.39	58.11	4.26	0.09	0.16	0.92
TH40-3-4	Station 13	1.74	0.11	34.52	5.28	0.06	0.10	1.61
TH40-4-1	Station 13	2.33	0.07	30.95	5.64	0.11	0.20	1.80
TH40-5-1	Station 13	3.31	0.15	16.70	11.77	0.10	0.17	1.63
TH40-5-2	Station 13	3.46	0.27	2.76	6.23	0.08	0.14	1.76
TH40-5-3	Station 13	3.61	0.15	1.34	8.32	0.07	0.09	1.31
TH40-6-1	Station 13	4.04	0.07	0.82	5.61	0.04	0.06	1.42
TH40-6-2	Station 13	4.19	0.00	0.72	8.36	0.04	0.07	1.64
TH40-6-3	Station 13	4.34	0.08	1.43	12.49	0.04	0.07	1.56
TH40-6-4	Station 13	4.49	0.07	2.50	19.47	0.04	0.07	1.64
TH40-6-5	Station 13	4.64	0.06	1.71	9.34	0.04	0.07	1.54
TH40-7-1	Station 13	4.95	0.06	1.49	4.91	0.05	0.08	1.57
TH40-7-2	Station 13	5.10	0.32	1.30	5.25	0.05	0.08	1.64
TH40-7-3	Station 13	5.25	0.35	1.34	6.73	0.05	0.07	1.64
TH40-7-4	Station 13	5.40	0.43	1.15	6.87	0.05	0.08	1.65
TH40-7-5	Station 13	5.55	0.48	1.13	8.30	0.04	0.07	1.67
TH40-8-1	Station 13	5.87	0.65	0.00	11.02	0.04	0.06	1.33
TH40-8-2	Station 13	6.02	0.62	0.00	8.90	0.04	0.05	1.45
TH40-8-3	Station 13	6.17	0.76	0.00	10.22	0.03	0.05	1.44
TH40-8-4	Station 13	6.32	0.85	0.00	9.69	0.04	0.06	1.39
TH44-1-1	Station 14	0.09	7.69	3.29	3.57	0.27	0.36	1.37
TH44-2-1	Station 14	0.35	4.67	15.74	3.47	0.26	0.36	1.38
TH44-2-2	Station 14	0.50	3.56	67.54	2.88	0.24	0.34	1.43
TH44-2-3	Station 14	0.65	2.98	209.38	4.61	0.23	0.32	1.43
TH44-3-1	Station 14	1.28	1.89	175.13	7.54	0.20	0.29	1.47
TH44-3-2	Station 14	1.43	1.82	124.68	4.97	0.14	0.22	1.60
TH44-3-3	Station 14	1.58	0.73	16.36	4.64	0.11	0.18	1.62
TH44-4-1	Station 14	2.16	0.32	1.99	1.33	0.14	0.23	1.61
TH44-4-2	Station 14	2.31	0.48	7.05	4.29	0.11	0.18	1.54
TH44-4-3	Station 14	2.46	0.53	19.42	4.07	0.15	0.25	1.66
TH44-4-4	Station 14	2.61	0.55	2.44	5.12	0.05	0.09	1.63
TH44-4-5	Station 14	2.76	0.32	2.21	6.38	0.06	0.10	1.61
TH44-5-1	Station 14	3.07	0.45	1.85	2.15	0.05	0.07	1.49

TH44-5-2	Station 14	3.22	0.62	4.10	6.23	0.06	0.09	1.60
TH44-5-3	Station 14	3.37	0.44	3.82	6.62	0.06	0.09	1.51
TH44-5-4	Station 14	3.52	0.32	3.26	8.13	0.06	0.10	1.56
TH44-5-5	Station 14	3.67	0.42	3.29	7.19	0.07	0.10	1.46
TH44-5-6	Station 14	3.82	0.45	6.83	4.11	0.12	0.18	1.48
TH44-6-1	Station 14	4.00	0.00	5.97	3.33	0.09	0.13	1.51
TH44-6-2	Station 14	4.15	0.60	8.40	4.03	0.08	0.13	1.65
TH44-6-3	Station 14	4.30	0.92	9.76	4.06	0.11	0.17	1.53
TH44-6-4	Station 14	4.45	1.52	2.30	6.03	0.10	0.16	1.56
TH44-6-5	Station 14	4.55	1.46	1.43	4.73	0.13	0.21	1.65
TH44-7-1	Station 14	4.95	2.11	1.44	7.91	0.08	0.11	1.42
TH44-7-2	Station 14	5.10	1.05	10.55	5.06	0.08	0.11	1.51
TH44-7-3	Station 14	5.35	1.76	1.62	6.36	0.07	0.09	1.29
TH-44-7-4	Station 14	5.50	2.52	1.73	7.63	0.08	0.11	1.51
TH44-8-1	Station 14	5.82	0.68	0.00	7.18	0.07	0.10	1.53
TH44-8-2	Station 14	5.97	2.35	0.00	7.51	0.07	0.11	1.67
TH44-8-3	Station 14	6.12	1.06	0.00	2.08	0.13	0.24	1.79
TH44-8-4	Station 14	6.27	3.91	1.57	7.63	0.11	0.18	1.67
TH44-9-1	Station 14	6.78	2.04	1.98	24.46	0.09	0.16	1.72
TH44-9-2	Station 14	6.93	1.67	2.88	5.00	0.12	0.18	1.60
TH44-9-3	Station 14	7.08	0.98	2.73	5.24	0.07	0.11	1.64
TH44-9-4	Station 14	7.43	2.55	3.28	8.41	0.14	0.26	1.90
TH44-10-1	Station 14	7.64	0.72	0.00	6.70	0.19	0.30	1.57
TH44-10-2	Station 14	7.64	2.42	0.00	6.04	0.18	0.30	1.67
TH44-10-3	Station 14	7.79	2.01	0.00	5.31	0.19	0.31	1.65
TH44-10-4	Station 14	7.94	1.59	0.00	5.93	0.18	0.30	1.66
TH44-10-5	Station 14	8.09	0.67	0.00	4.60	0.19	0.31	1.65
TH44-10-6	Station 14	8.24	0.74	0.00	5.60	0.18	0.28	1.59
TH43-1-1	Station 15	0.10	14.96	177.37	4.00	0.21	0.34	1.62
TH43-2-1	Station 15	0.35	2.11	333.55	4.10	0.20	0.33	1.66
TH43-2-2	Station 15	0.50	2.21	80.23	3.49	0.23	0.37	1.63
TH43-2-3	Station 15	0.67	2.07	9.65	3.96	0.21	0.34	1.65
TH43-2-4	Station 15	0.82	1.24	5.67	2.39	0.17	0.30	1.71
TH43-3-1	Station 15	1.26	1.00	16.65	2.91	0.16	0.26	1.68
TH43-3-2	Station 15	1.41	1.20	12.05	3.65	0.16	0.23	1.44
TH43-3-3	Station 15	1.56	0.65	8.55	4.00	0.06	0.08	1.48
TH43-4-1	Station 15	2.16	0.36	7.44	4.32	0.05	0.07	1.36
TH43-4-2	Station 15	2.31	0.51	11.04	4.25	0.05	0.07	1.34
TH43-4-3	Station 15	2.46	0.67	5.72	3.34	0.07	0.11	1.46
TH43-4-4	Station 15	2.61	0.62	3.80	2.89	0.06	0.09	1.47
TH43-5-1	Station 15	3.07	0.32	21.64	4.49	0.09	0.14	1.56
TH43-5-2	Station 15	3.22	0.78	16.51	4.40	0.09	0.16	1.73
TH43-5-3	Station 15	3.37	0.66	13.16	3.49	0.10	0.15	1.57
TH43-5-4	Station 15	3.52	0.56	8.99	4.06	0.10	0.18	1.83
TH43-5-5	Station 15	3.67	0.33	3.07	4.72	0.07	0.14	1.81

TH43-6-1	Station 15	3.99	0.47	5.09	4.34	0.08	0.13	1.62
TH43-6-2	Station 15	4.29	0.38	1.41	1.00	0.09	0.14	1.63
TH43-6-3	Station 15	4.44	0.67	1.61	5.38	0.07	0.12	1.68
TH43-6-4	Station 15	4.59	0.77	0.00	6.29	0.06	0.10	1.56
TH43-7-1	Station 15	4.90	0.74	0.00	5.97	0.06	0.08	1.37
TH43-7-2	Station 15	5.05	0.80	0.00	5.76	0.06	0.09	1.50
TH43-7-3	Station 15	5.20	0.68	0.00	5.33	0.06	0.08	1.41
TH43-7-4	Station 15	5.35	0.53	0.00	4.97	0.06	0.07	1.21

Appendix G: Cumulative Bromide Mass Plots

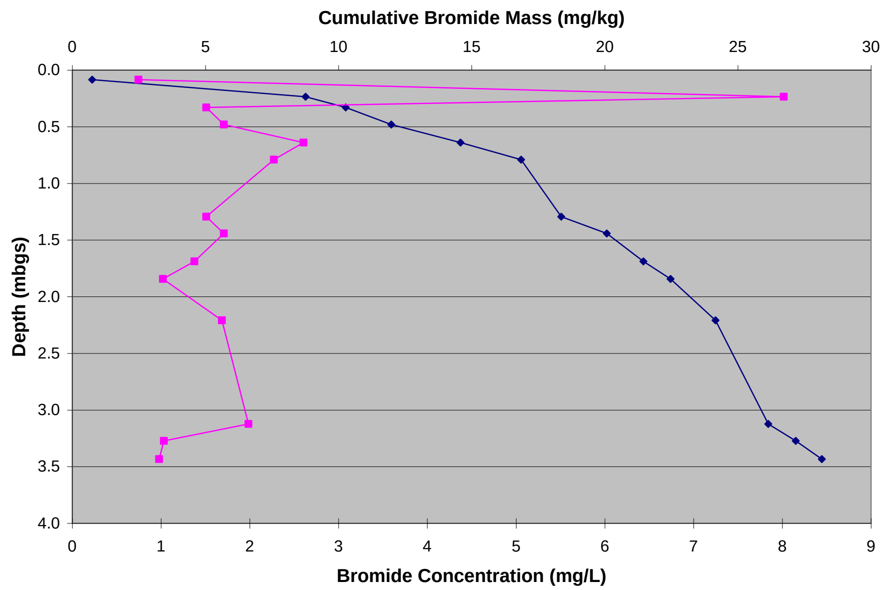


Figure G.1. Cumulative bromide mass and bromide concentration at Station 1 (TH50).

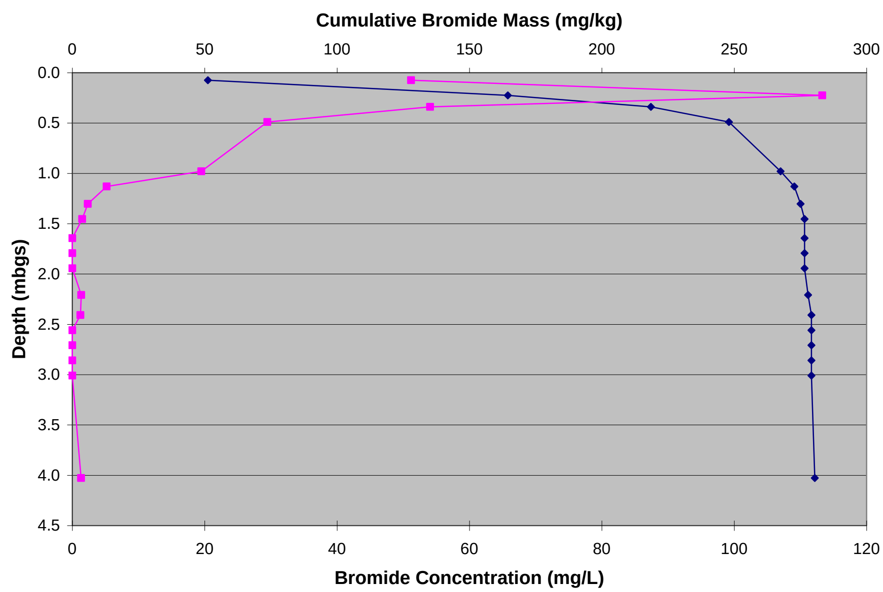


Figure G.2. Cumulative bromide mass and bromide concentration at Station 2 (TH45).

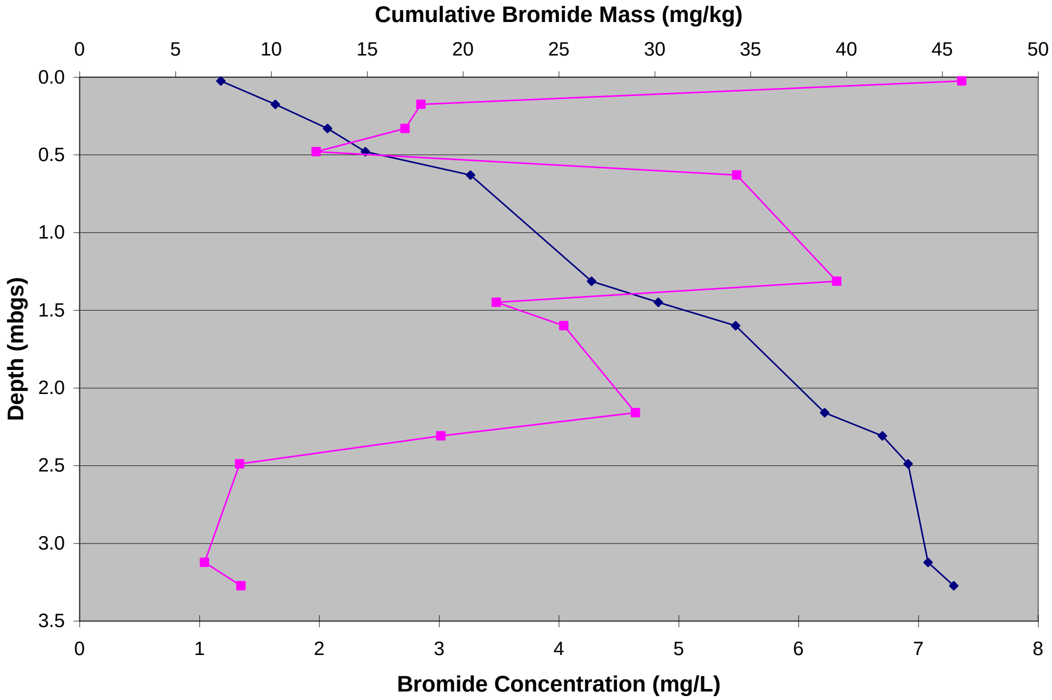


Figure G.3. Cumulative bromide mass and bromide concentration at Station 3 (TH52).

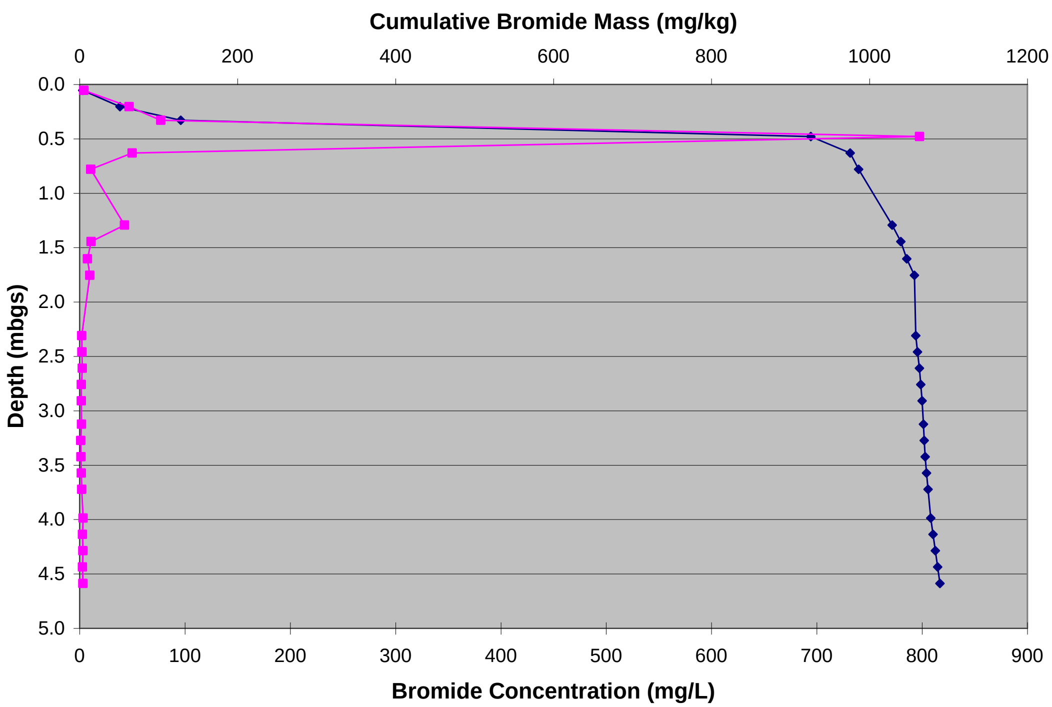


Figure G.4. Cumulative bromide mass and bromide concentration at Station 4 (TH39).

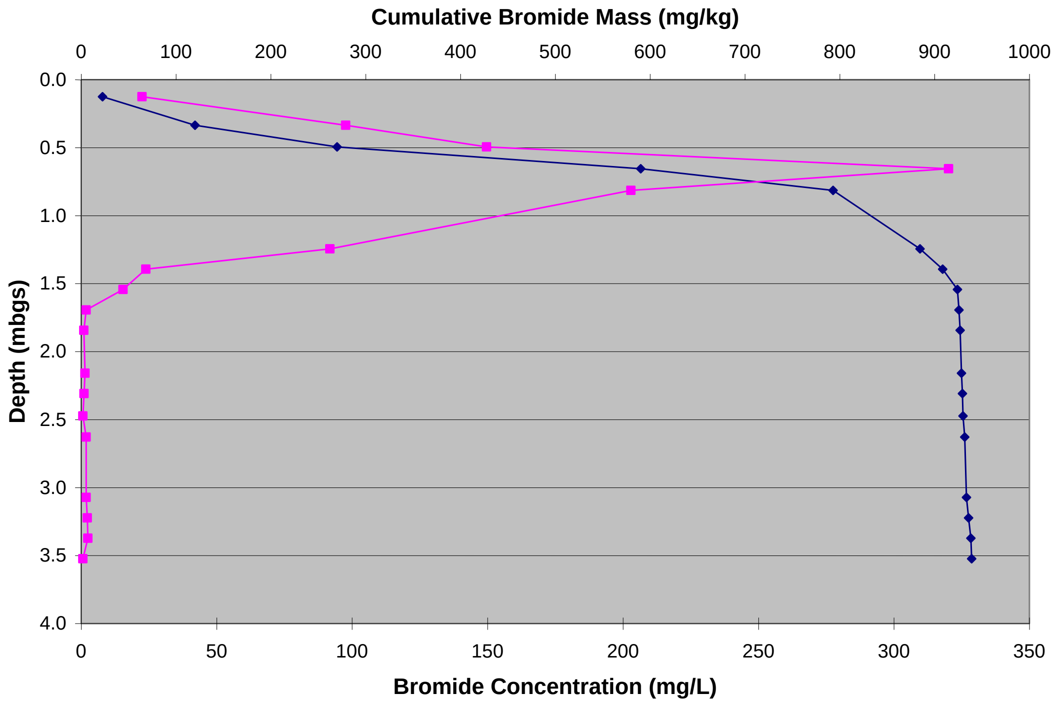


Figure G.5. Cumulative bromide mass and bromide concentration at Station 6 (TH49).

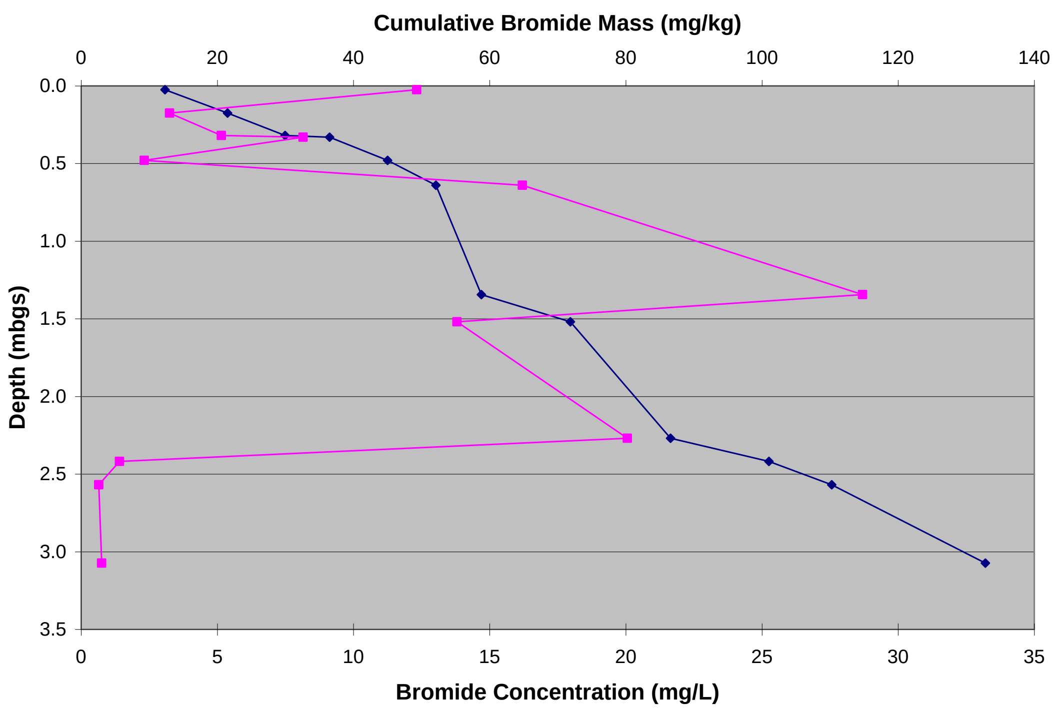


Figure G.6. Cumulative bromide mass and bromide concentration at Station 9 (TH49).

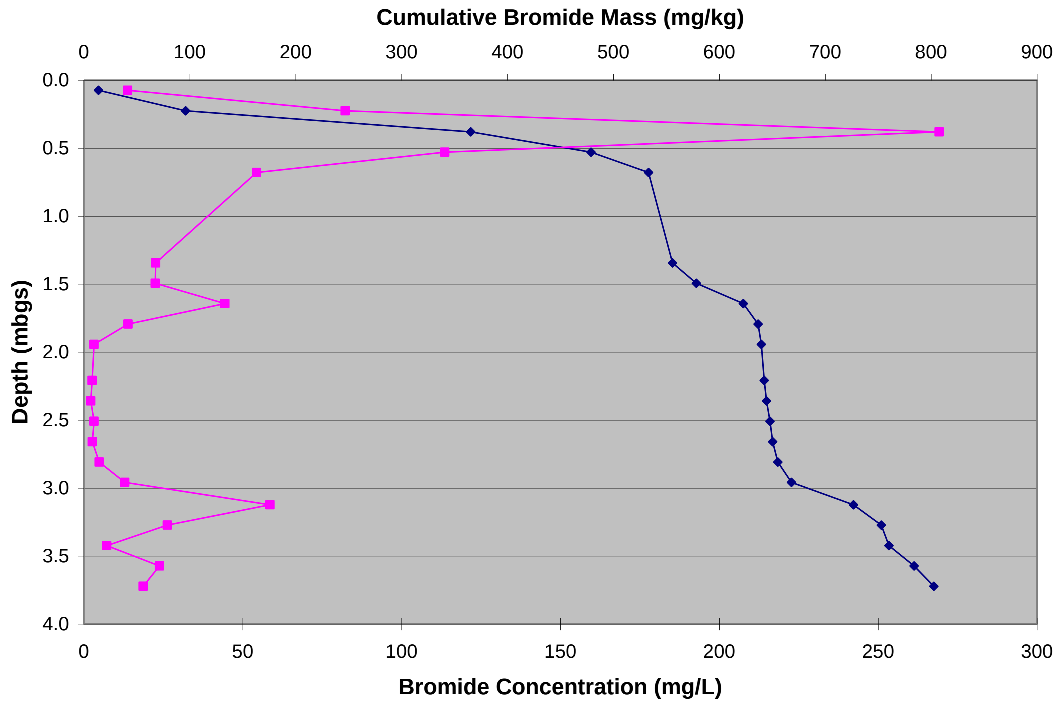


Figure G.7. Cumulative bromide mass and bromide concentration at Station 10 (TH42).

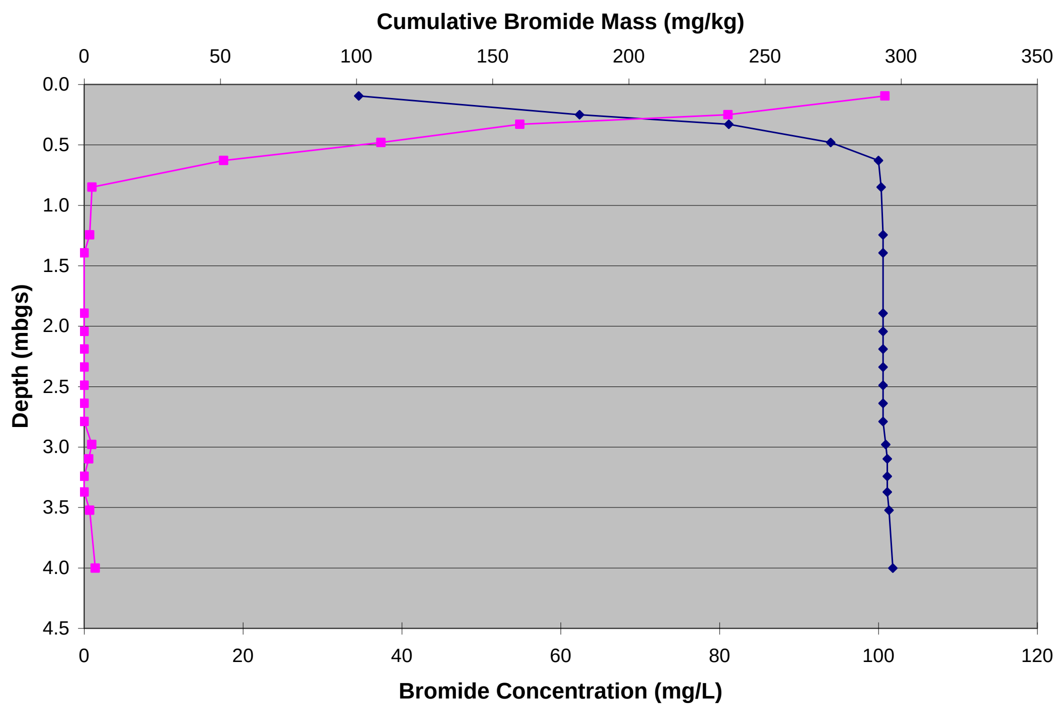


Figure G.8. Cumulative bromide mass and bromide concentration at Station 11 (TH51).

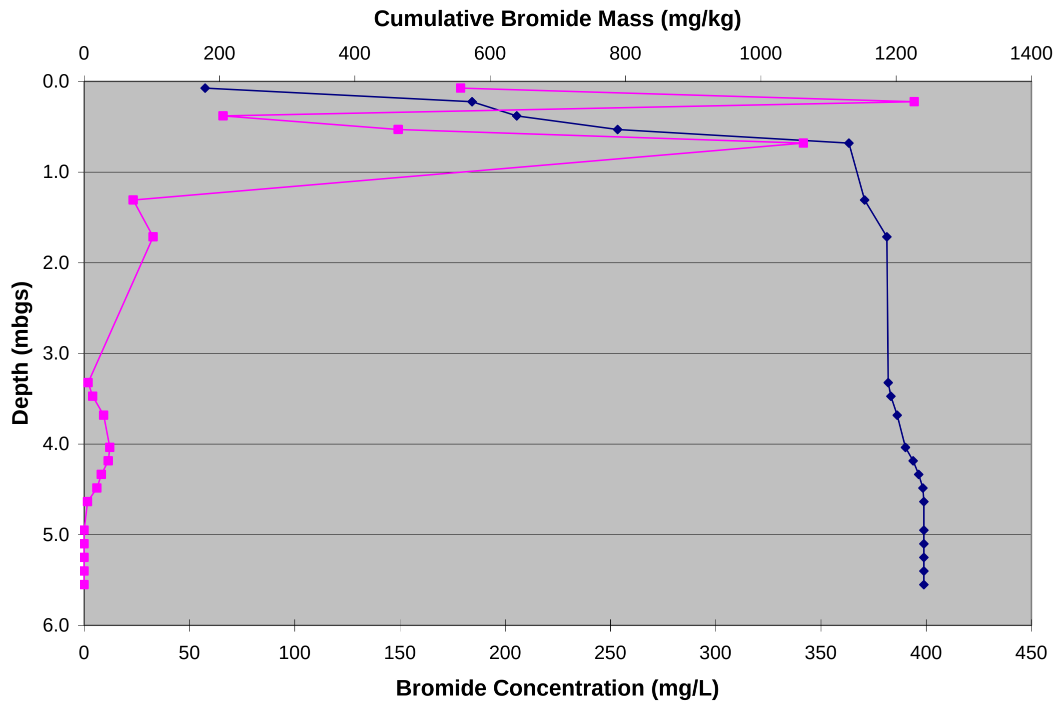


Figure G.9. Cumulative bromide mass and bromide concentration at Station 12 (TH41).

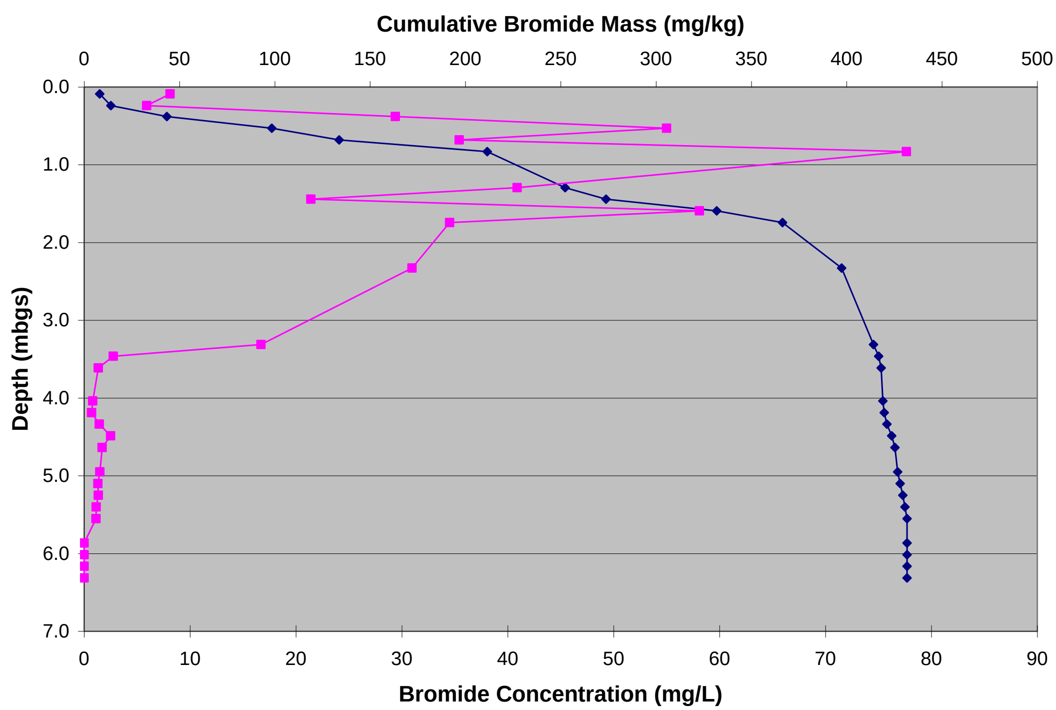


Figure G.10. Cumulative bromide mass and bromide concentration at Station 13 (TH40).

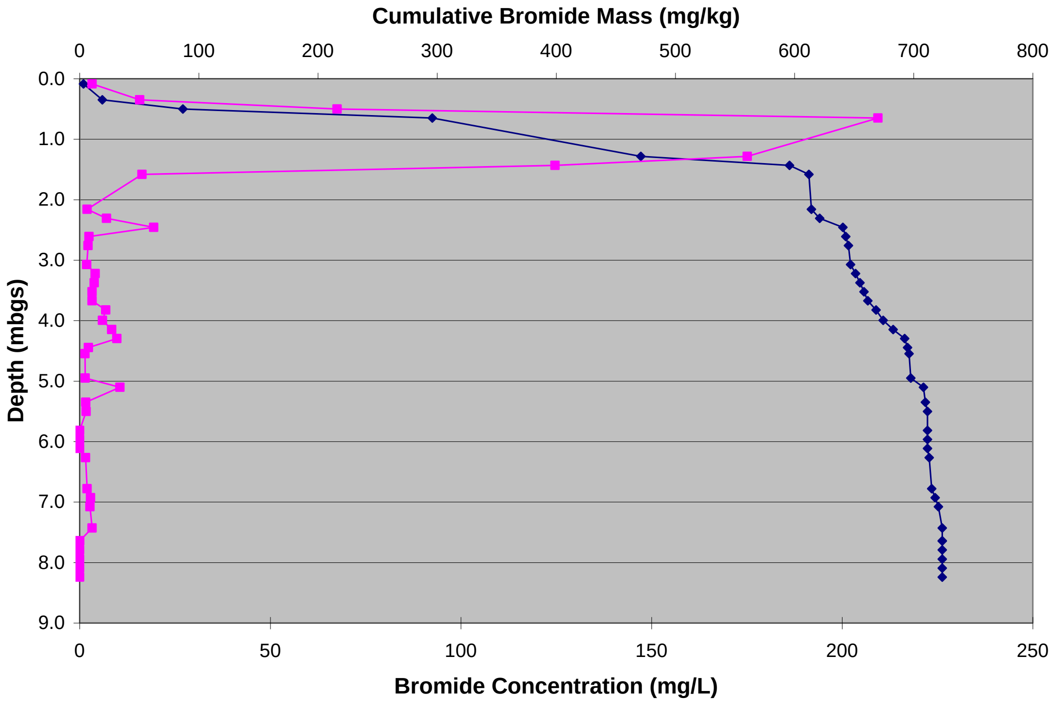


Figure G.11. Cumulative bromide mass and bromide concentration at Station 14 (TH44).

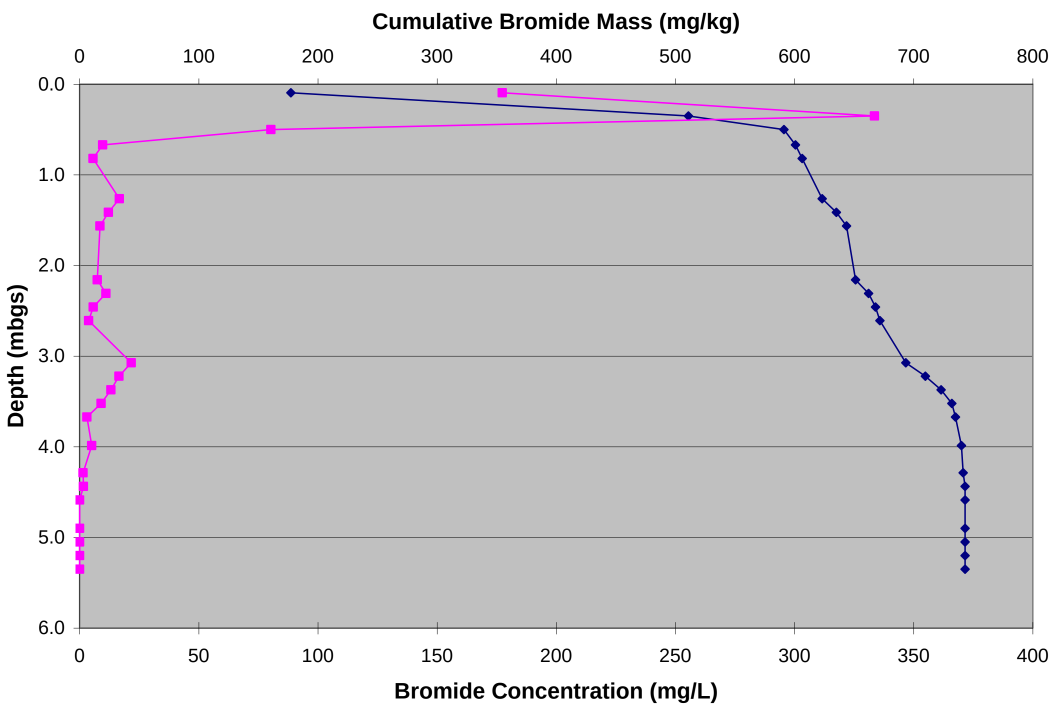


Figure G.12. Cumulative bromide mass and bromide concentration at Station 15 (TH43).

Appendix H: Volumetric Moisture Contents

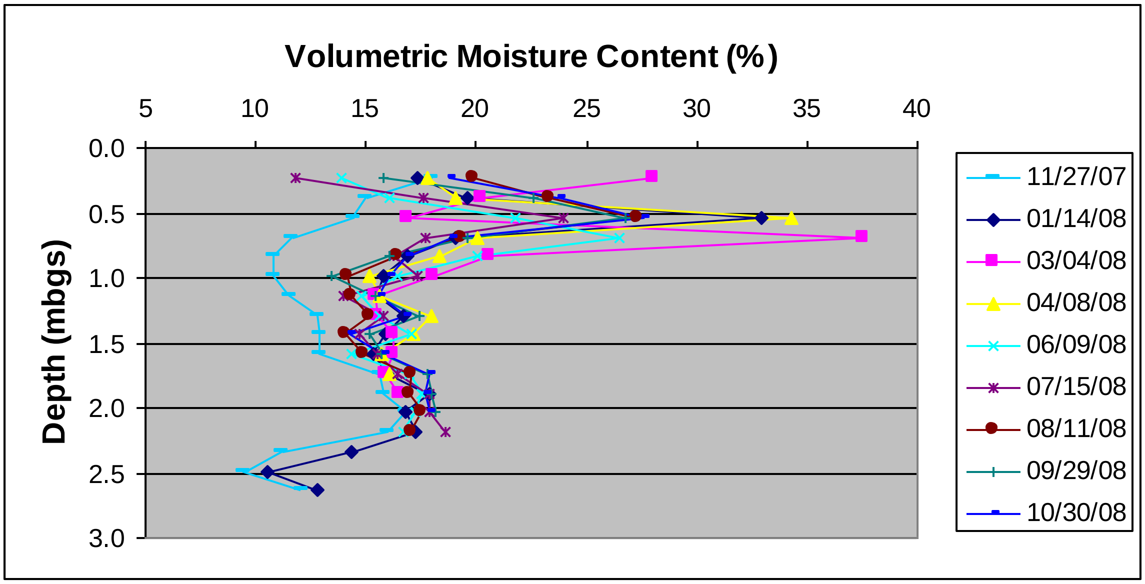


Figure H.1. Station 1 (AT13) neutron probe measured soil moisture profile.

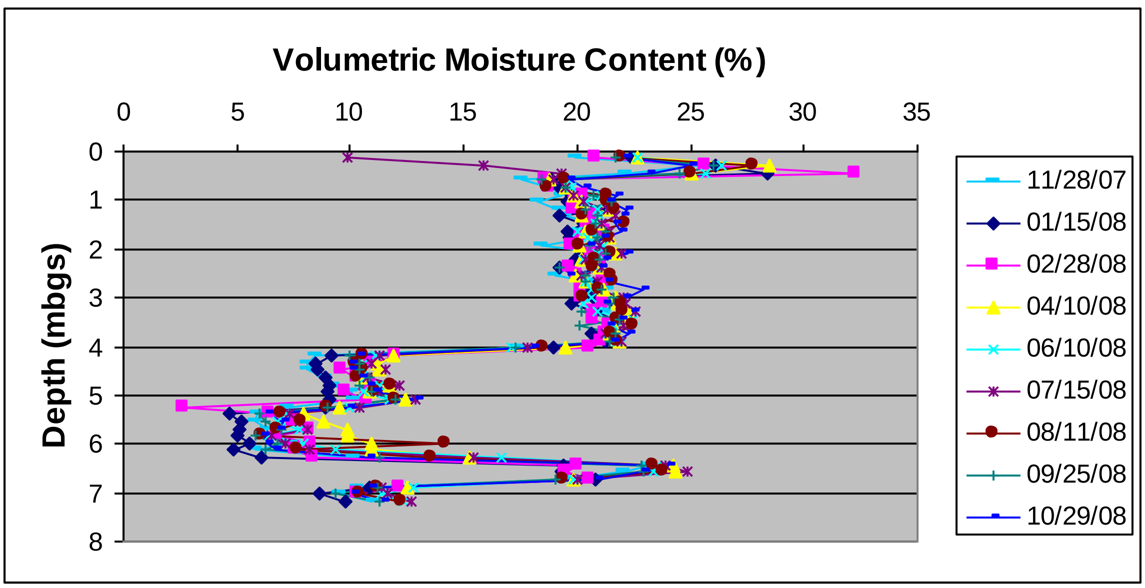


Figure H.2. Station 2 (AT11) neutron probe measured soil moisture profile.

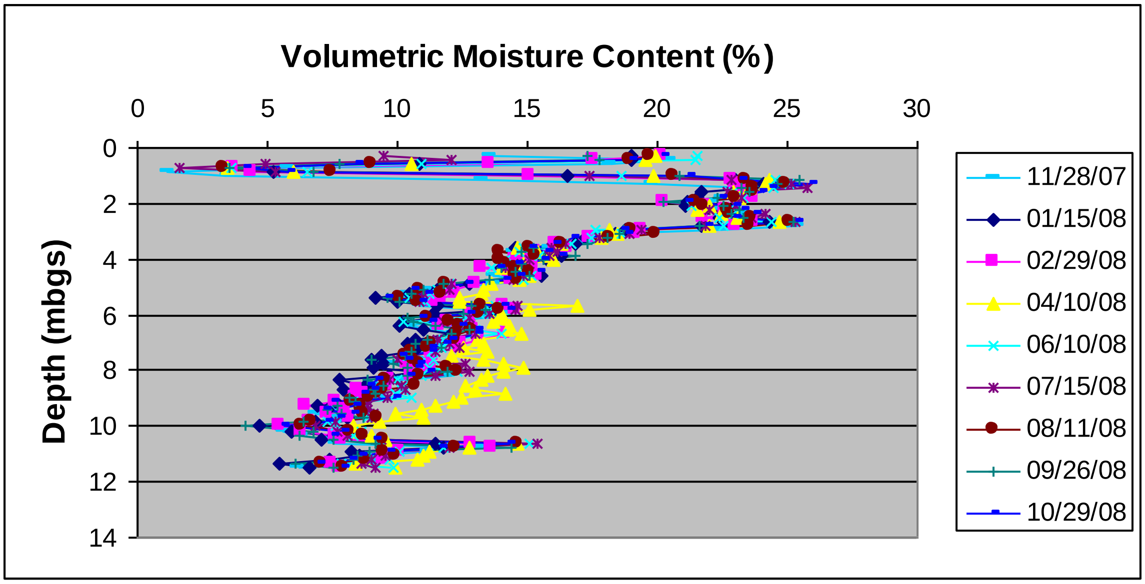


Figure H.3. Station 3 (AT9) neutron probe measured soil moisture profile.

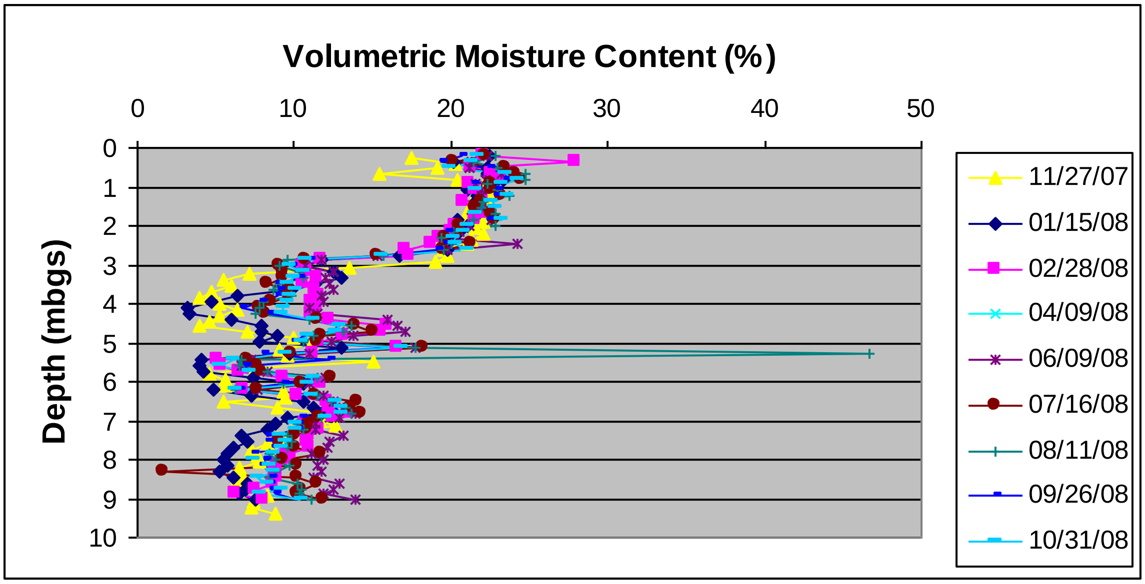


Figure H.4. Station 4 (AT14) neutron probe measured soil moisture profile.

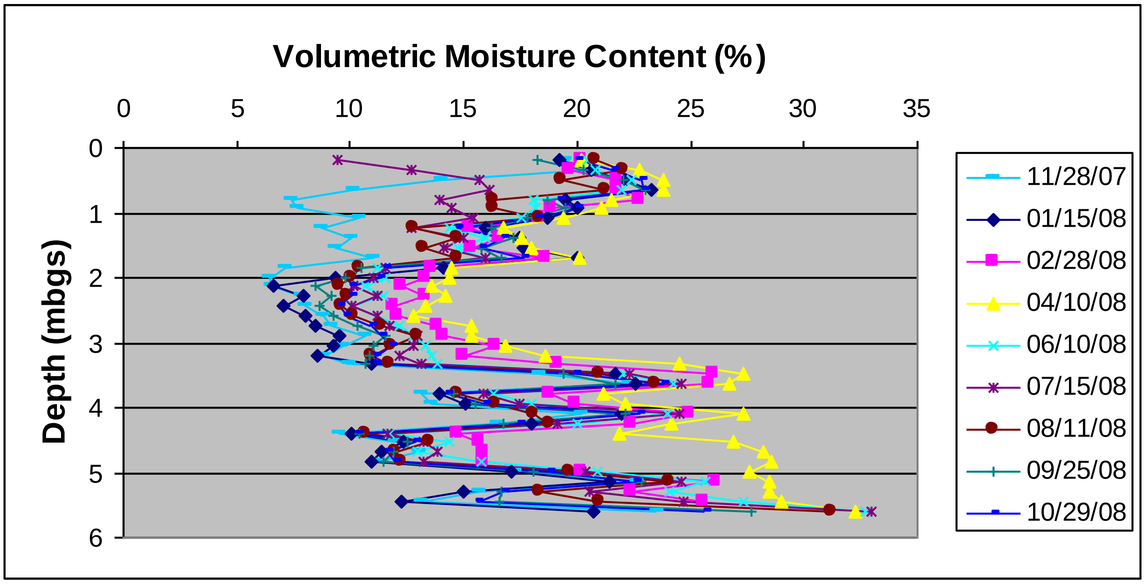


Figure H.5. Station 5 (AT3) neutron probe measured soil moisture profile.

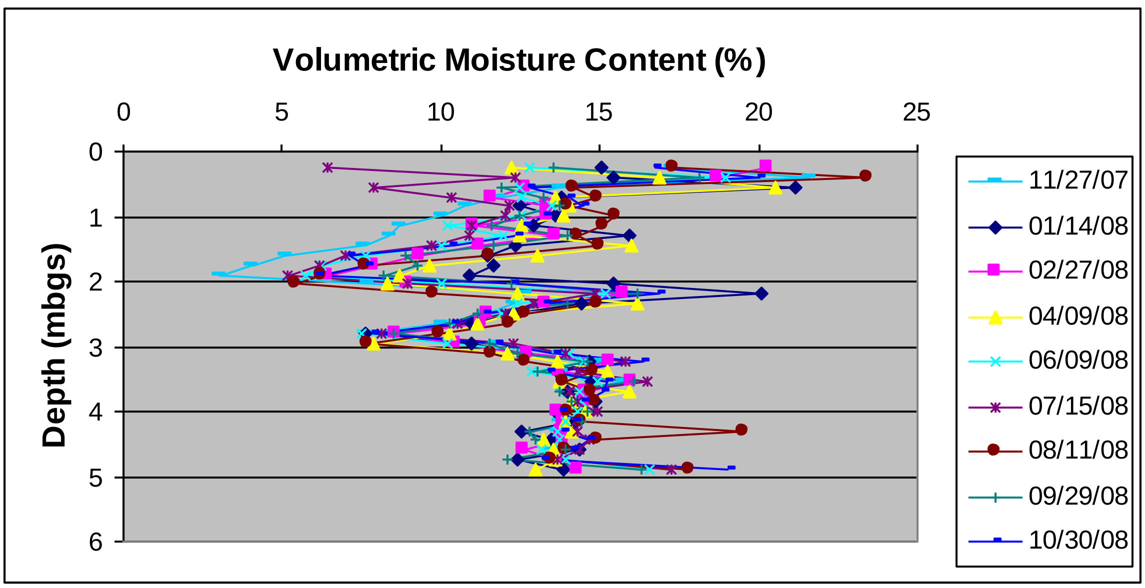


Figure H.6. Station 6 (AT12) neutron probe measured soil moisture profile.

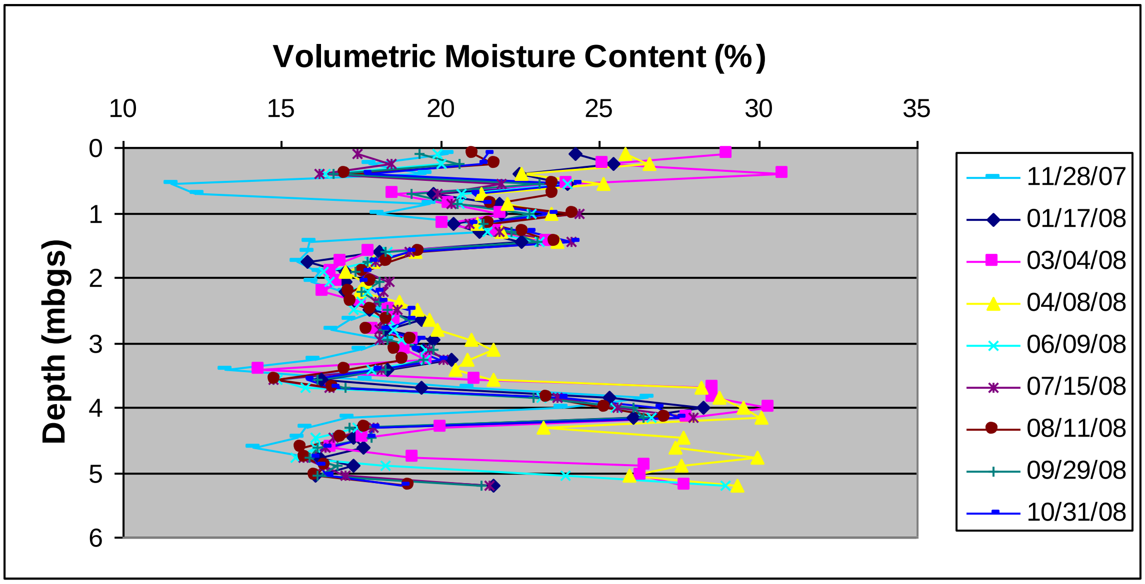


Figure H.7. Station 7 (AT15) neutron probe measured soil moisture profile.

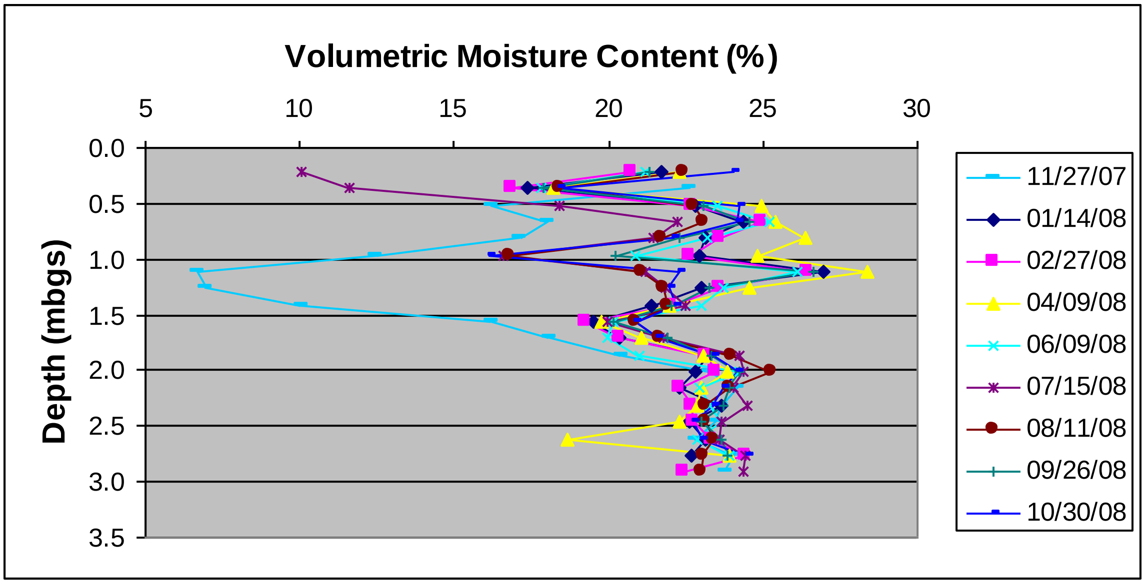


Figure H.8. Station 8 (AT6) neutron probe measured soil moisture profile.

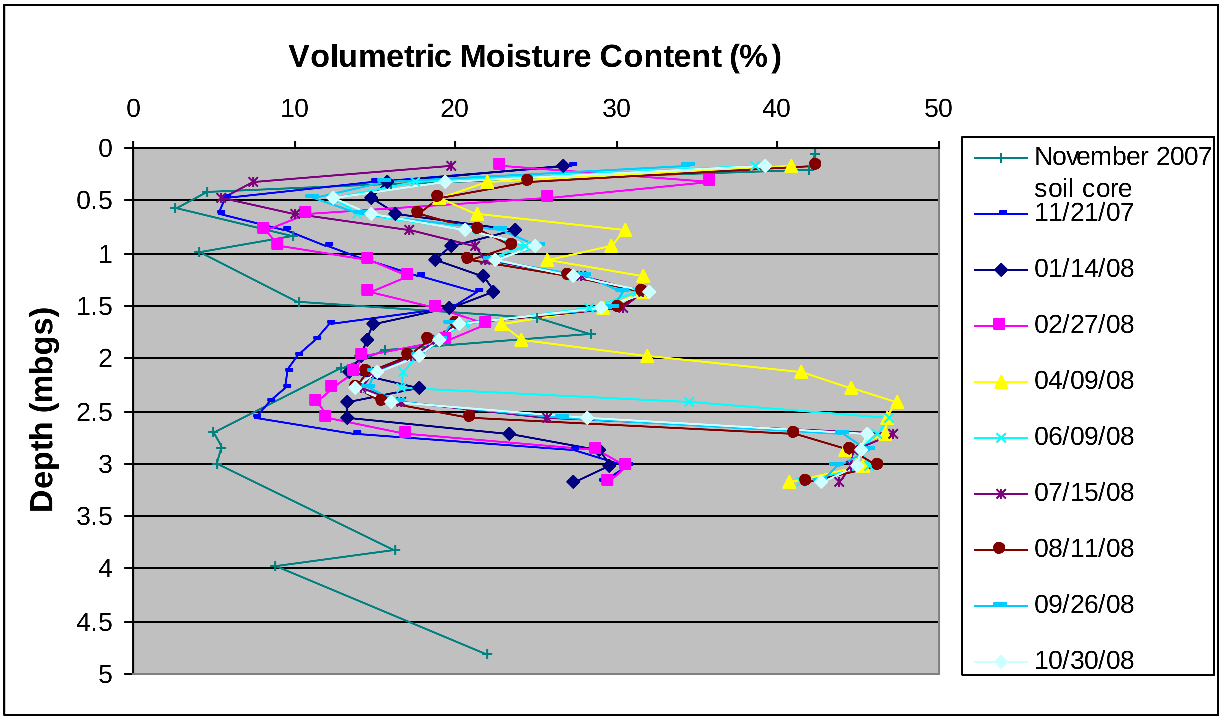


Figure H.9. Station 9 (AT20) neutron probe measured soil moisture profile. Laboratory measured moisture profile of core from AT20 installation included for reference.

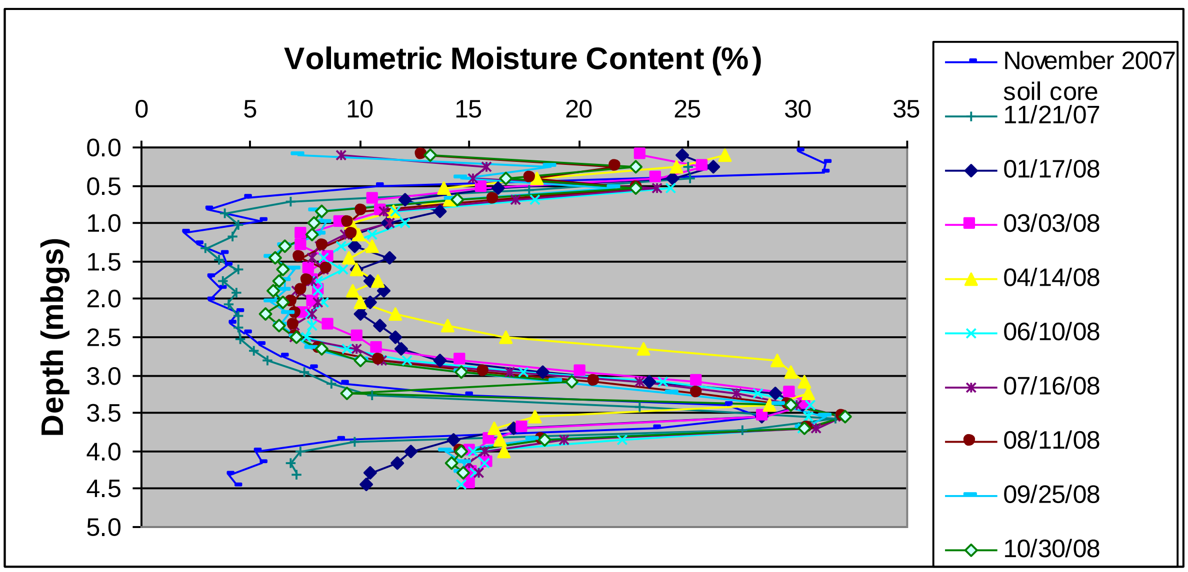


Figure H.10. Station 10 (AT21) neutron probe measured soil moisture profile. Laboratory measured moisture profile of core from AT21 installation included for reference.

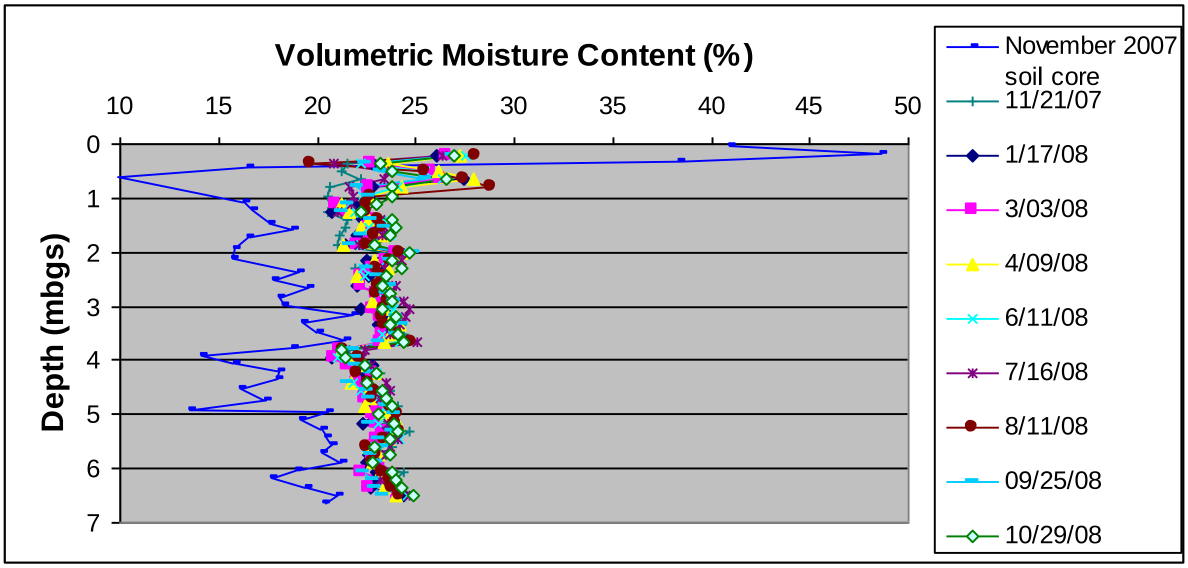


Figure H.11. Station 11 (AT22) neutron probe measured soil moisture profile. Laboratory measured moisture profile of core from AT21 installation included for reference.

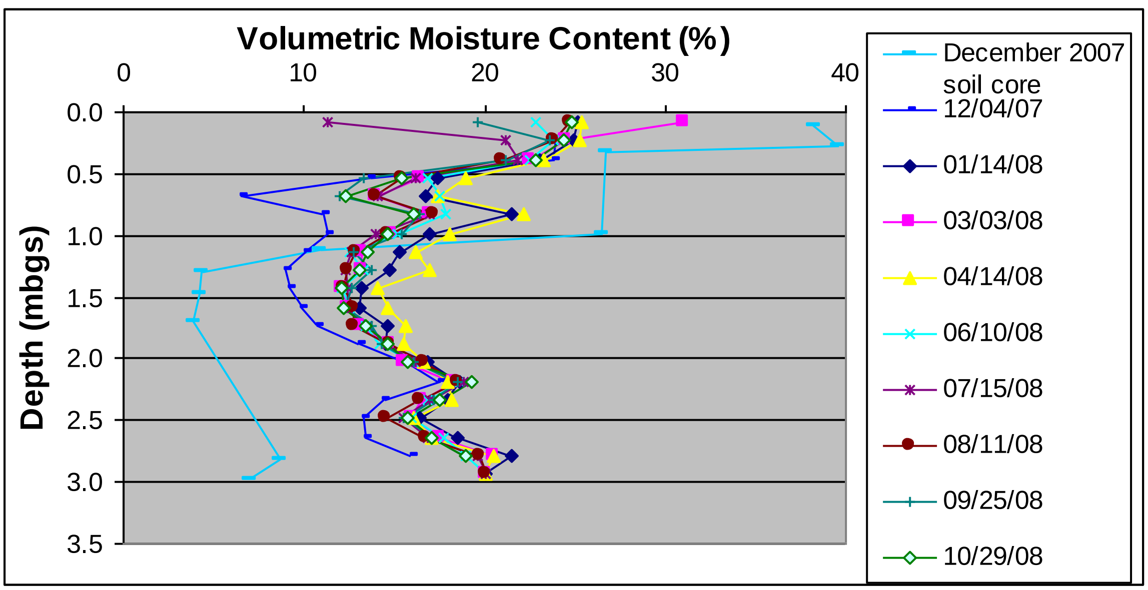


Figure H.12. Station 12 (AT23) neutron probe measured soil moisture profile. Laboratory measured moisture profile of core from AT23 installation included for reference.

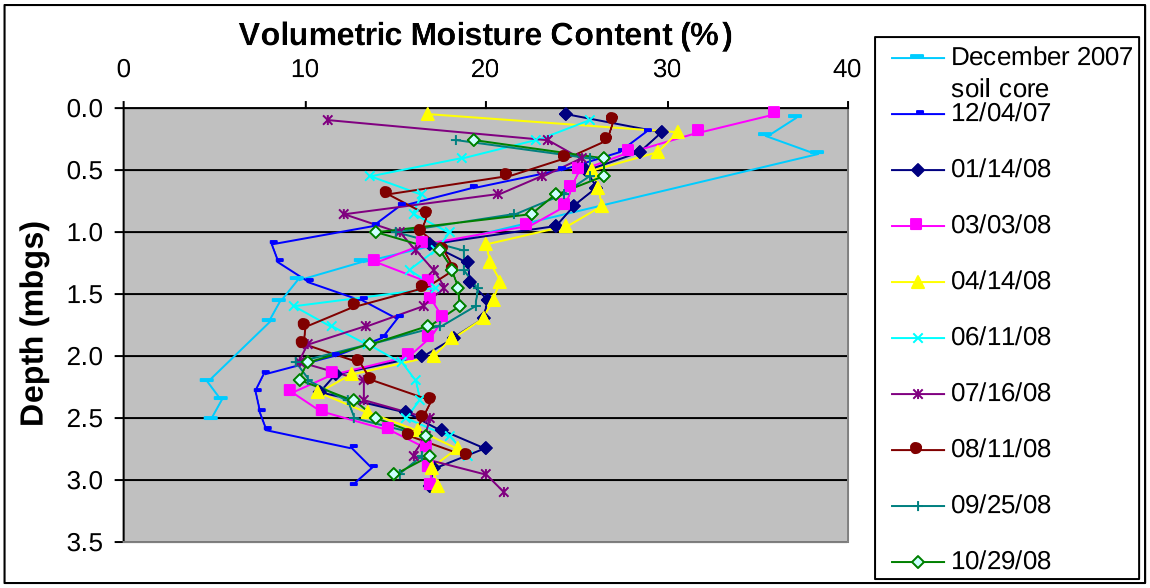


Figure H.13. Station 13 (AT24) neutron probe measured soil moisture profile. Laboratory measured moisture profile of core from AT14 installation included for reference.

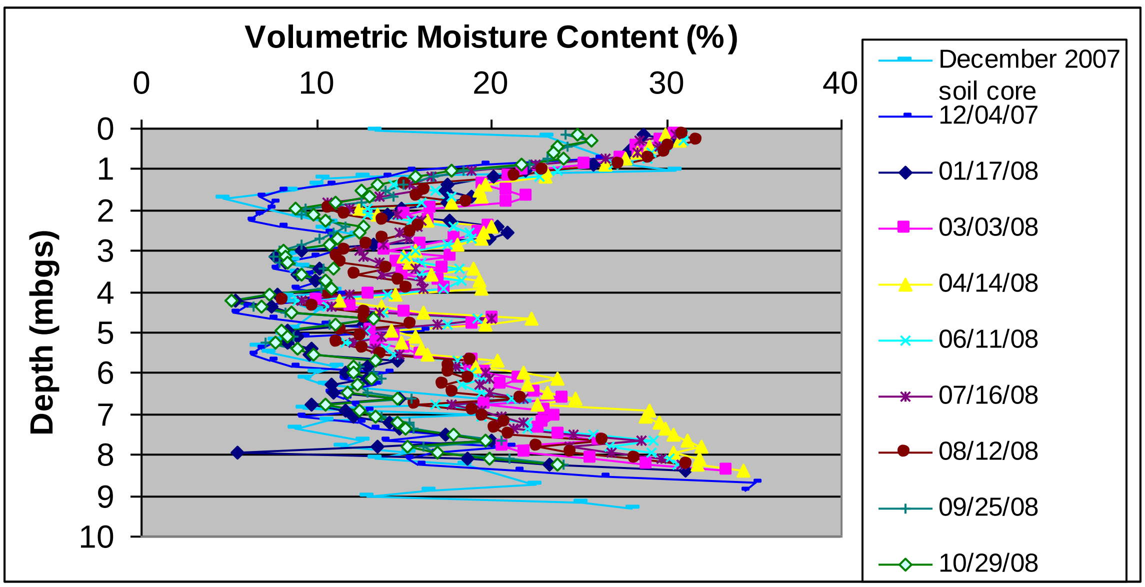


Figure H.14. Station 14 (AT25) neutron probe measured soil moisture profile. Laboratory measured moisture profile of core from AT25 installation included for reference.

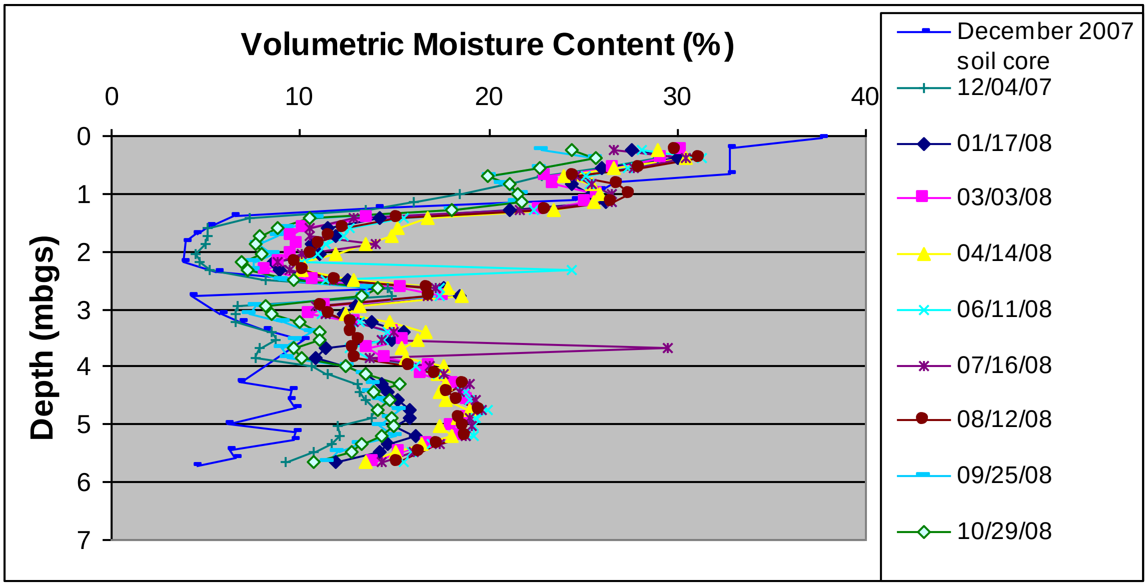


Figure H.15. Station 15 (AT26) neutron probe measured soil moisture profile. Laboratory measured moisture profile of core from AT26 installation included for reference.

Appendix I: Supplementary Porewater Nitrate Plots (May 2008)

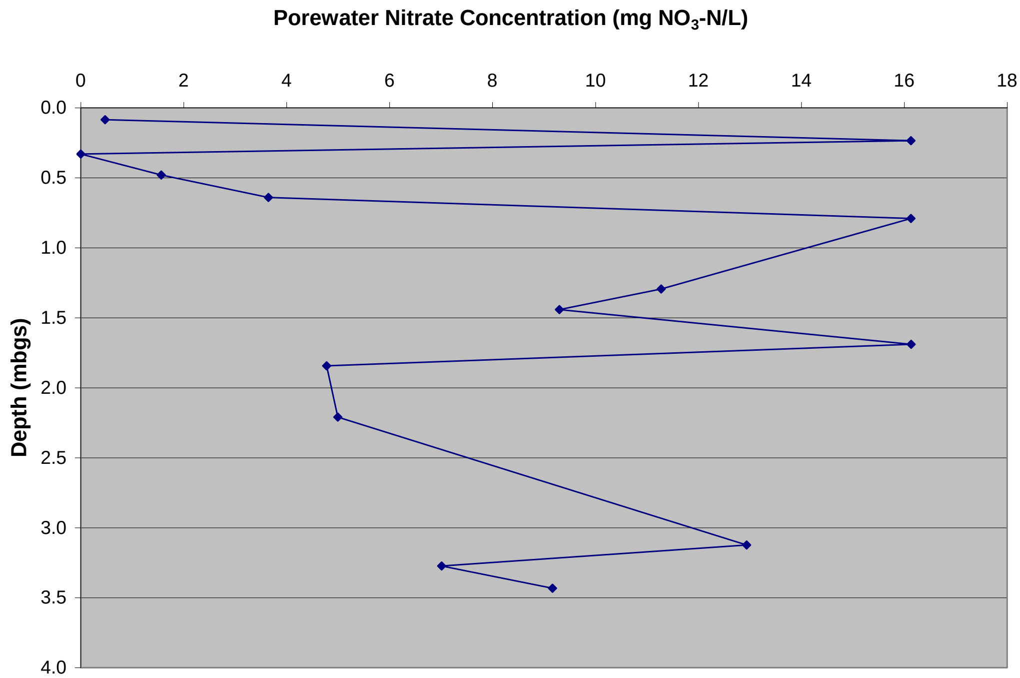


Figure I.1. Porewater nitrate concentration versus depth at Station 1.

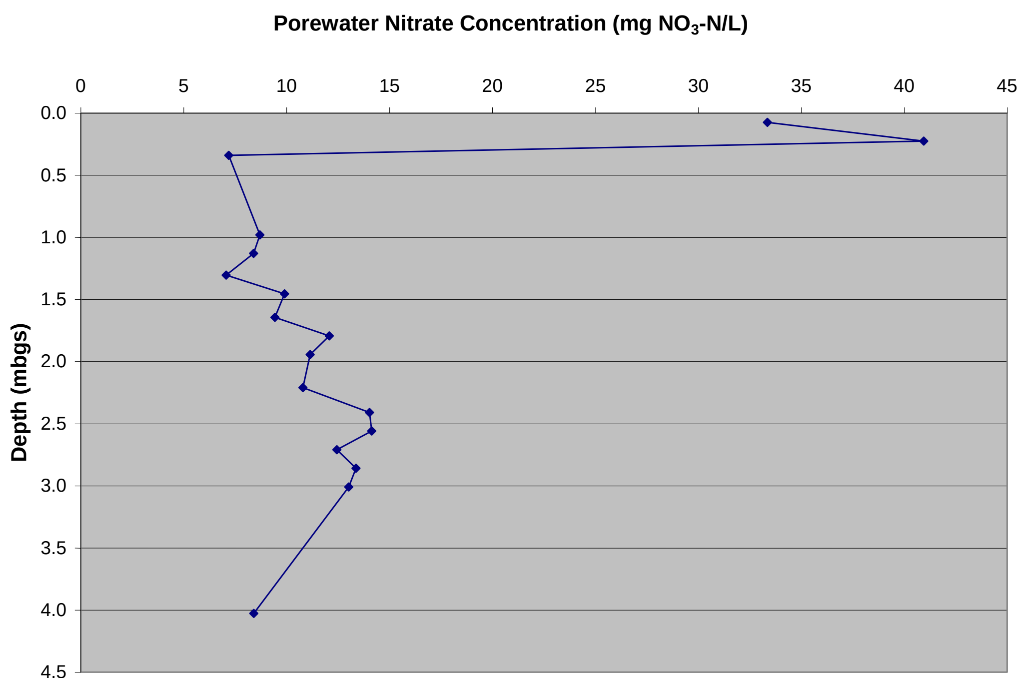


Figure I.2. Porewater nitrate concentration versus depth at Station 2.

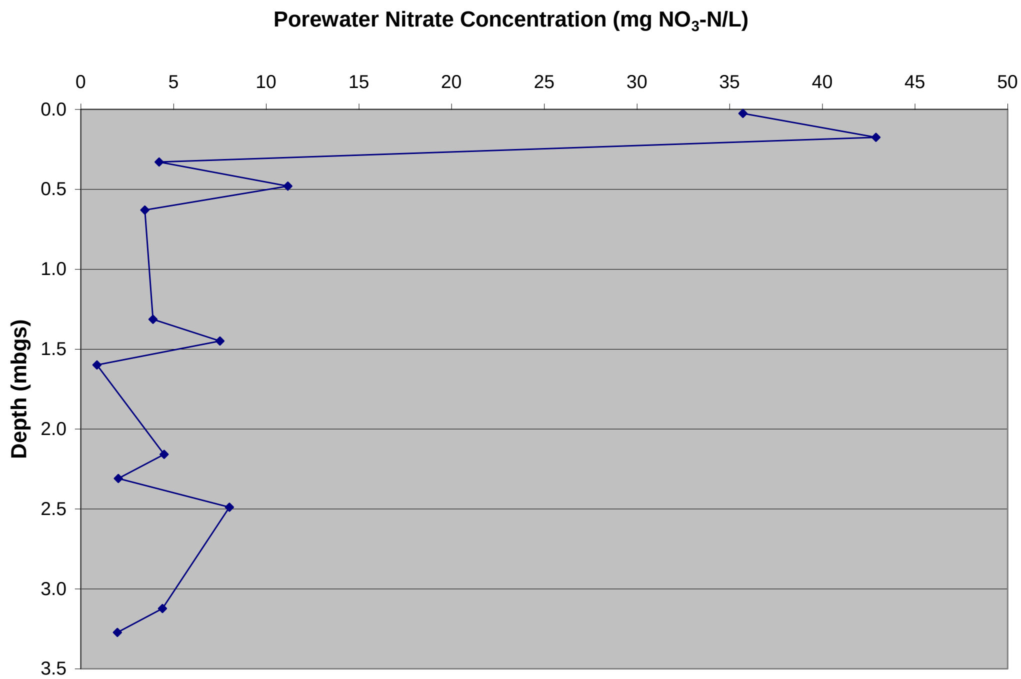


Figure I.3. Porewater nitrate concentration versus depth at Station 3.

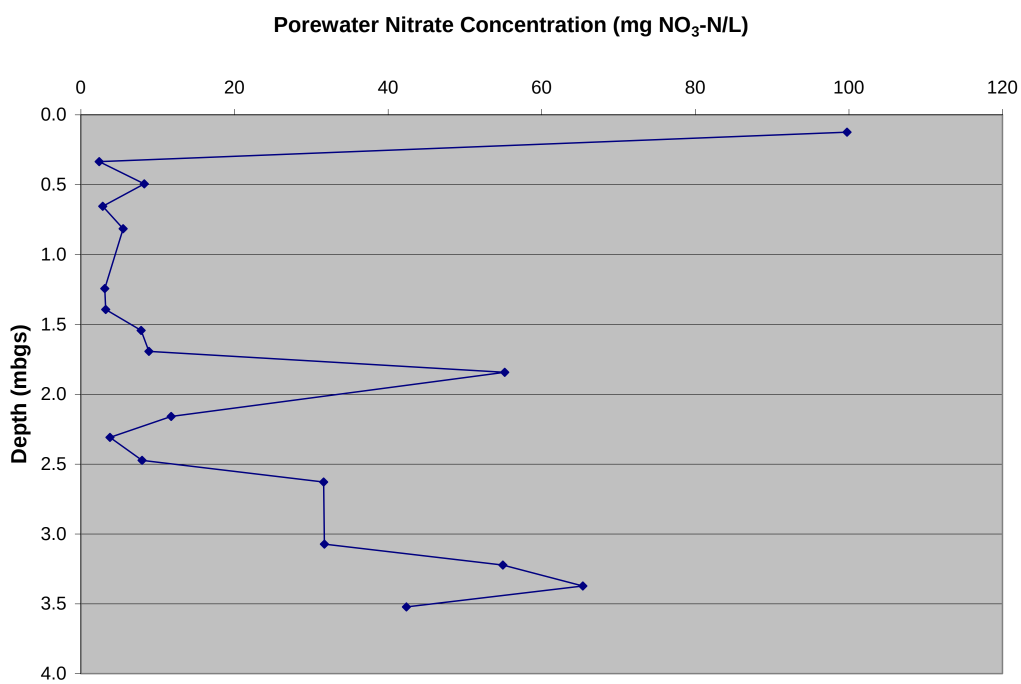


Figure I.4. Porewater nitrate concentration versus depth at Station 6.

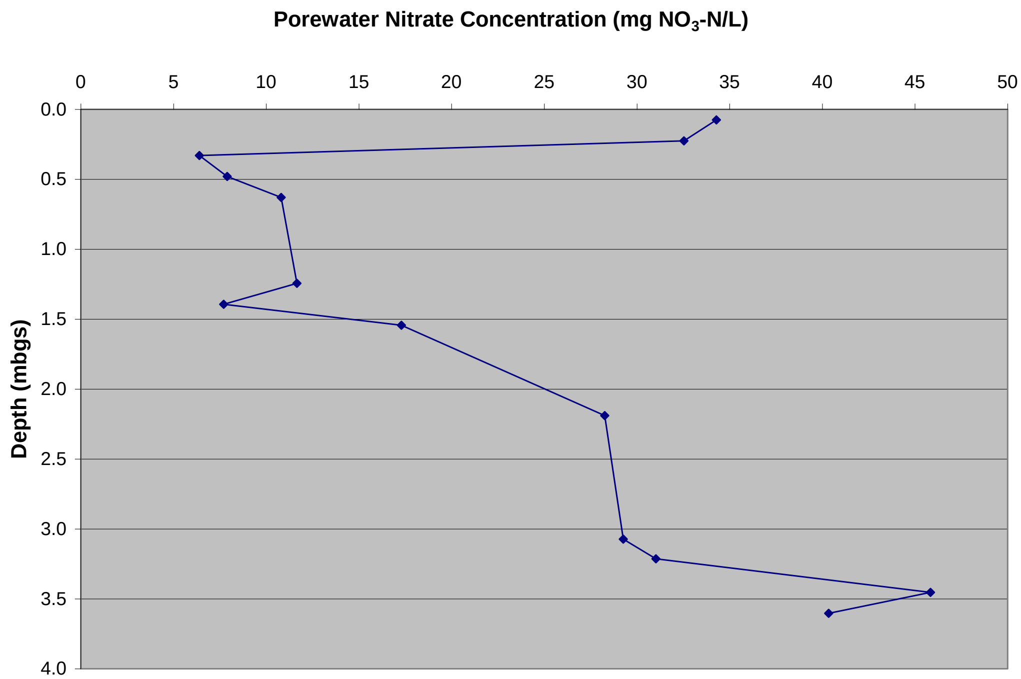


Figure I.5. Porewater nitrate concentration versus depth at Station 8.

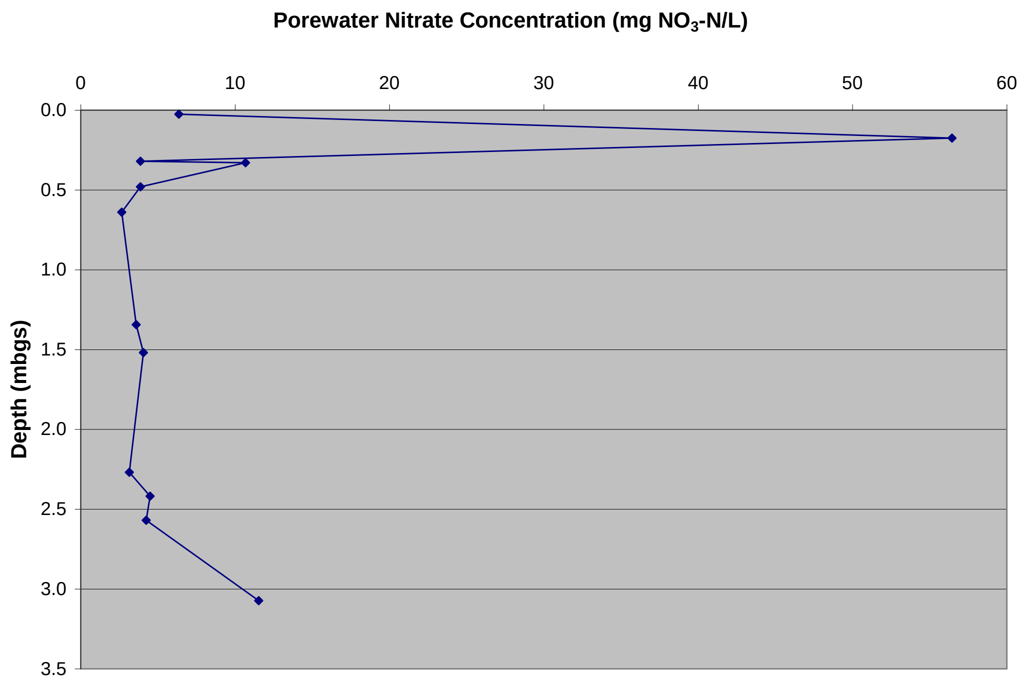


Figure I.6. Porewater nitrate concentration versus depth at Station 9.

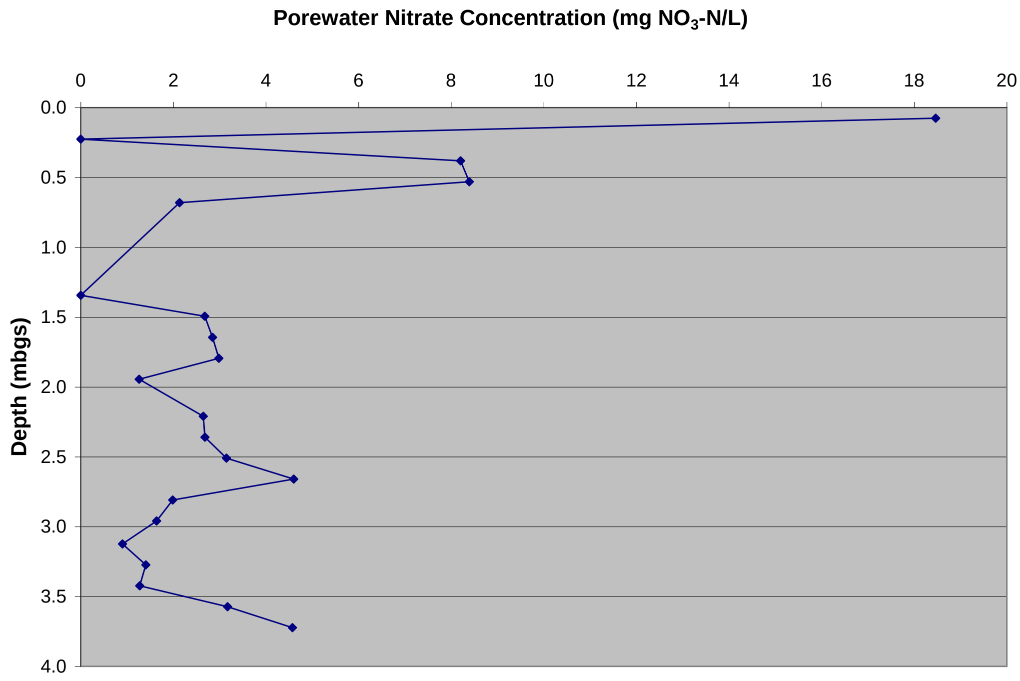


Figure I.7. Porewater nitrate concentration versus depth at Station 10.

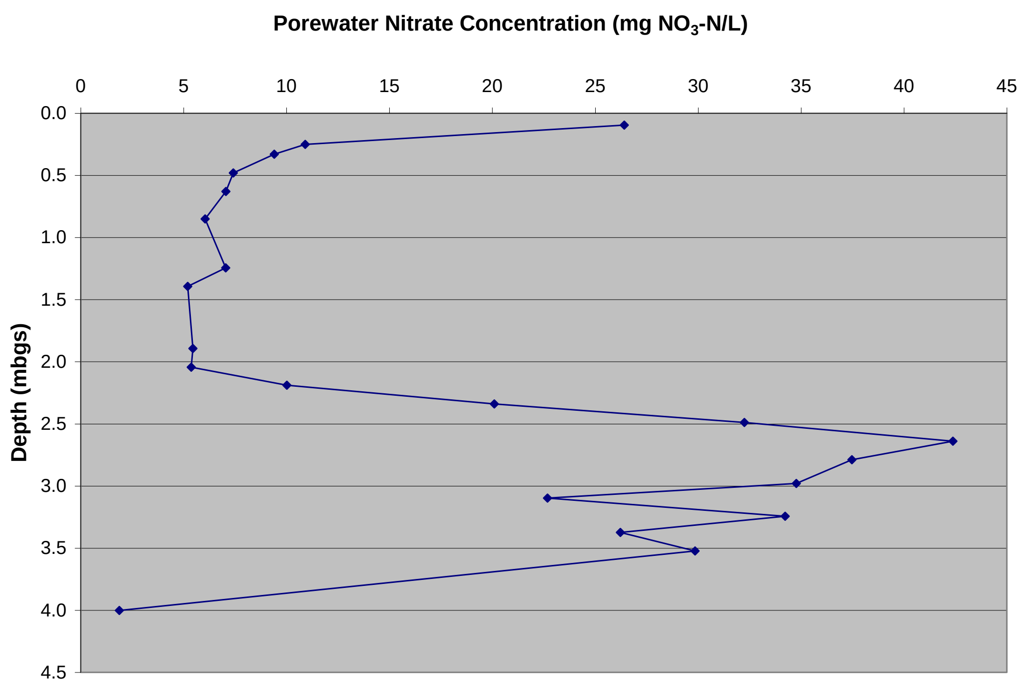


Figure I.8. Porewater nitrate concentration versus depth at Station 11.

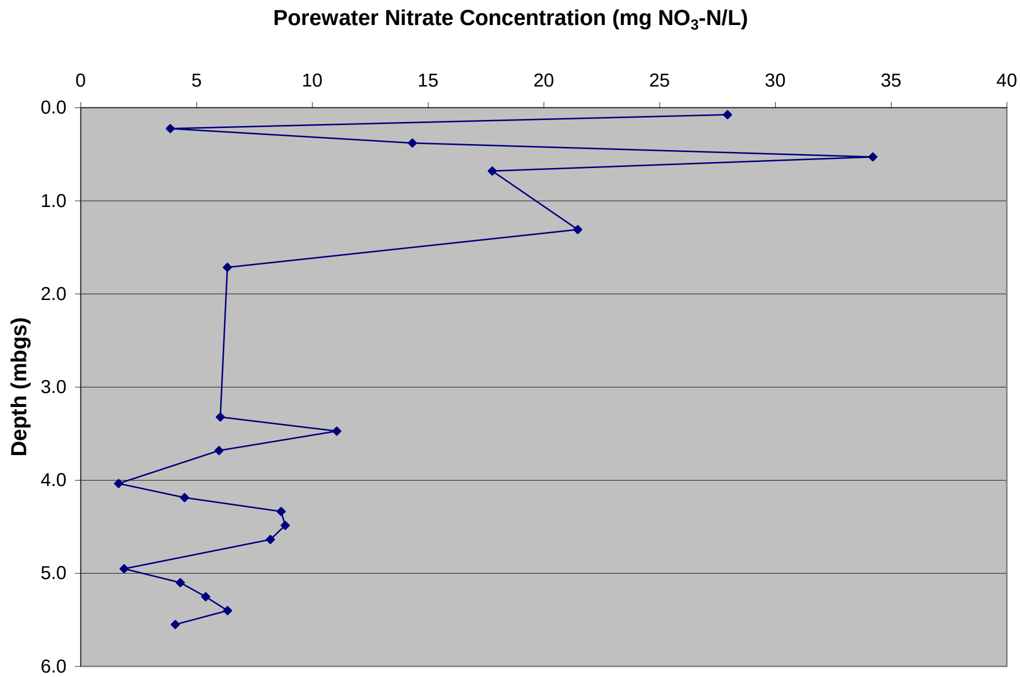


Figure I.9. Porewater nitrate concentration versus depth at Station 12.

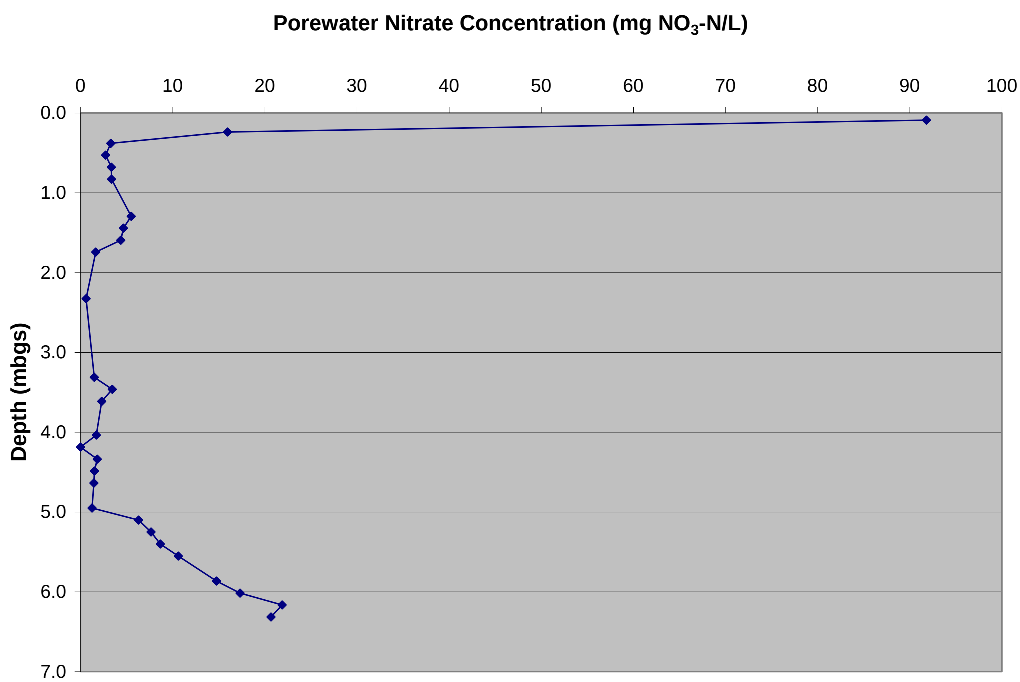


Figure I.10. Porewater nitrate concentration versus depth at Station 13.

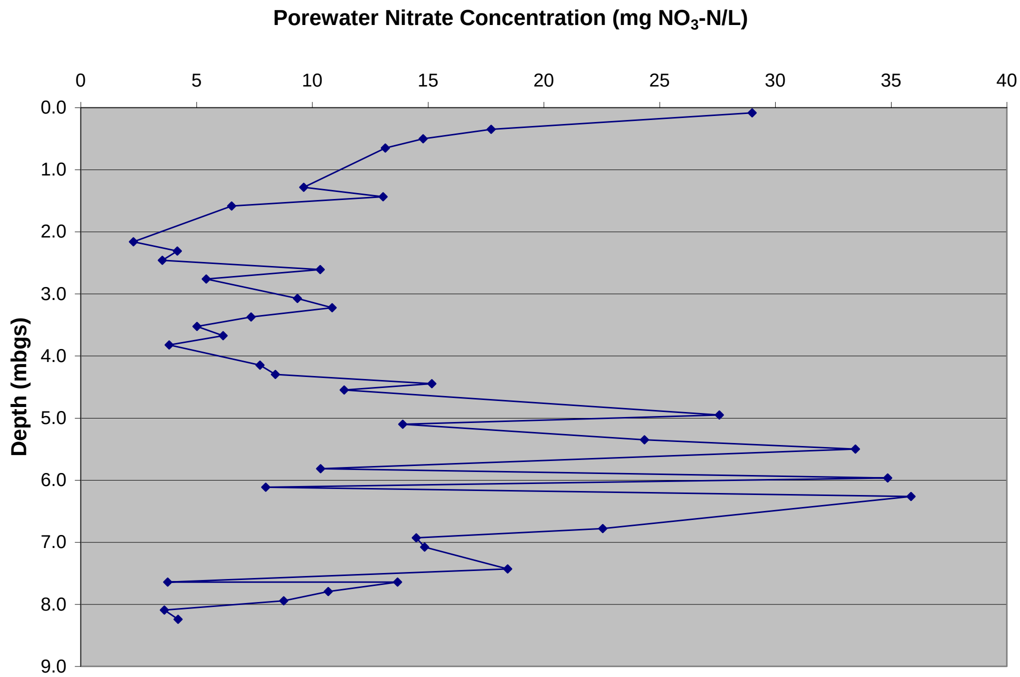


Figure I.11. Porewater nitrate concentration versus depth at Station 14.

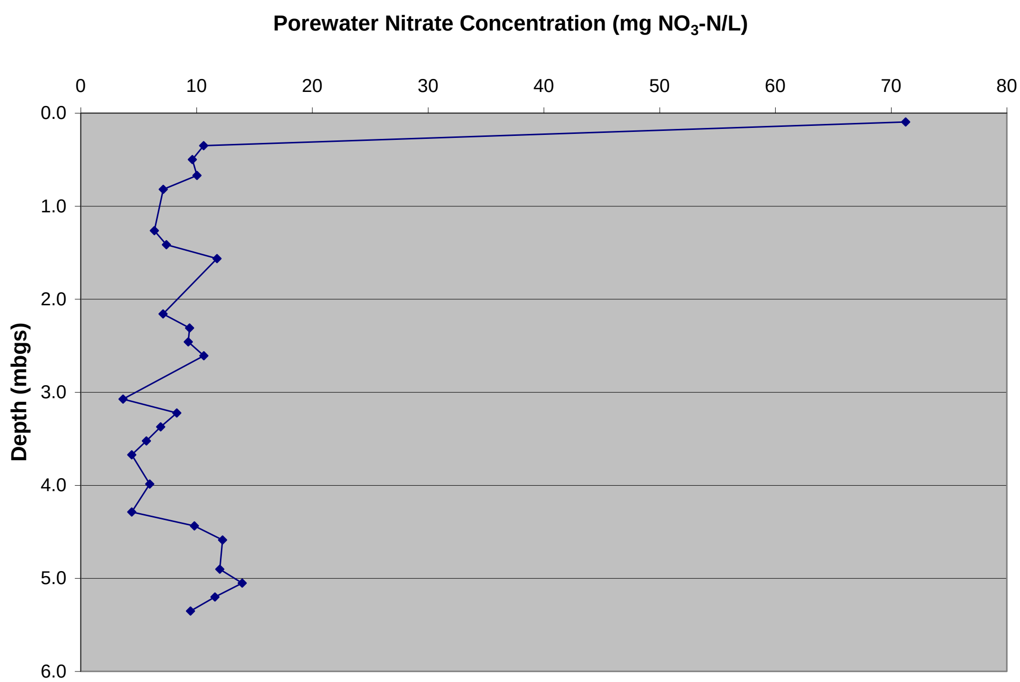


Figure I.12. Porewater nitrate concentration versus depth at Station 15.

Appendix J: Supplementary Cumulative Soil Nitrate Plots

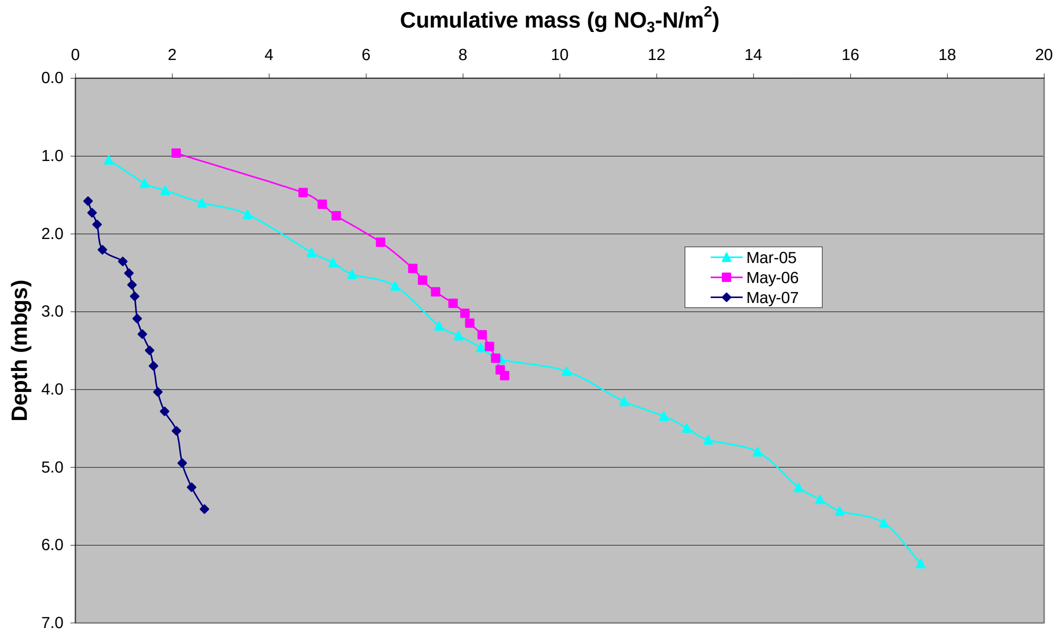


Figure J.1. Cumulative nitrate mass versus depth at Station 7.

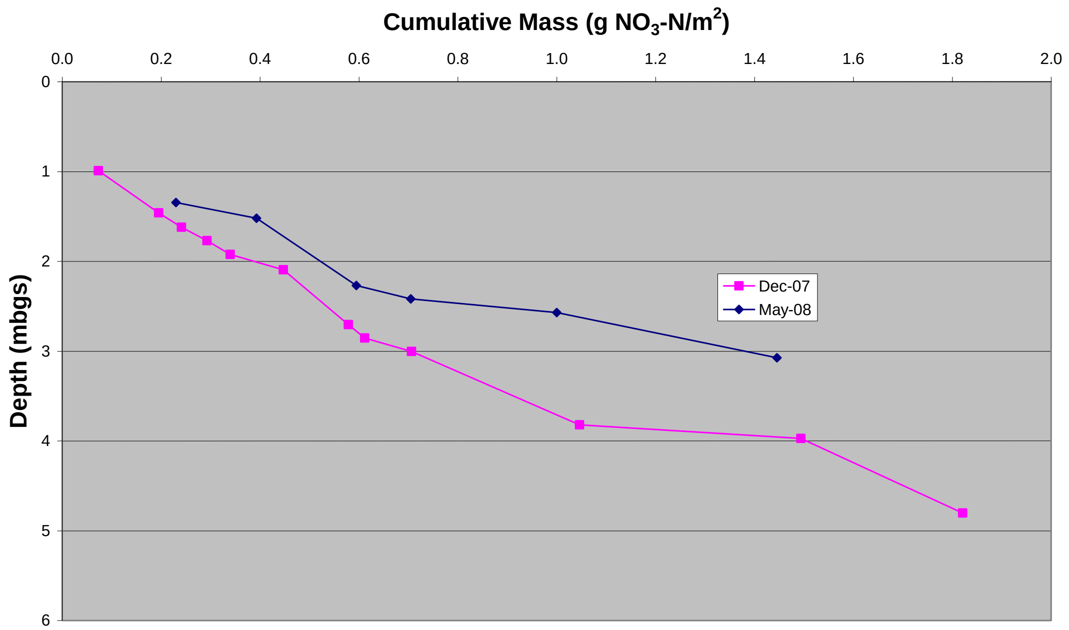


Figure J.2. Cumulative nitrate mass versus depth at Station 9.

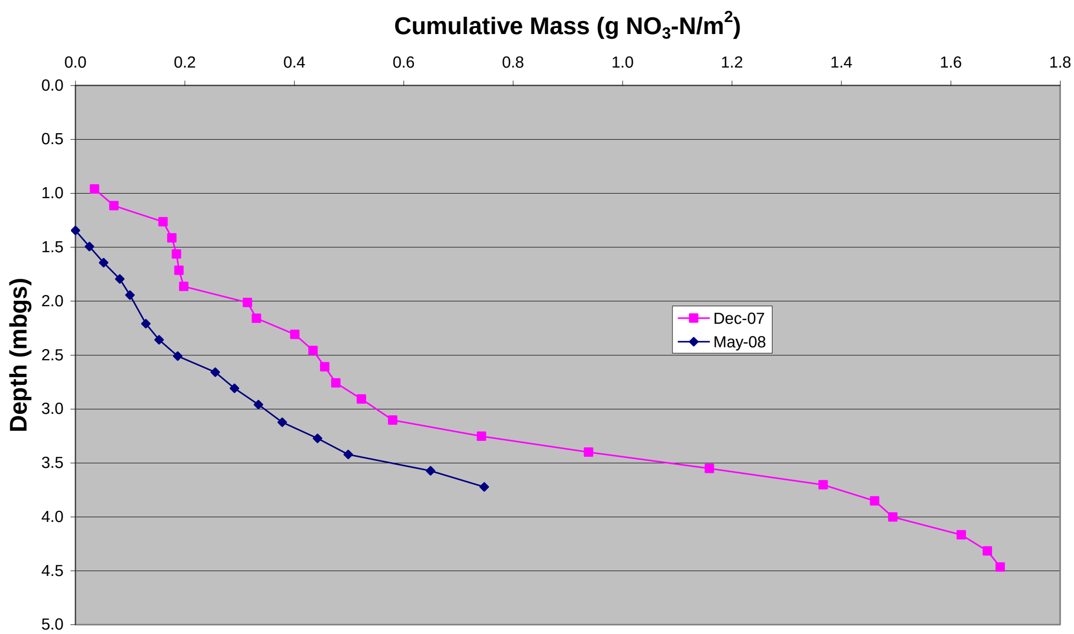


Figure J.3. Cumulative nitrate mass versus depth at Station 10.

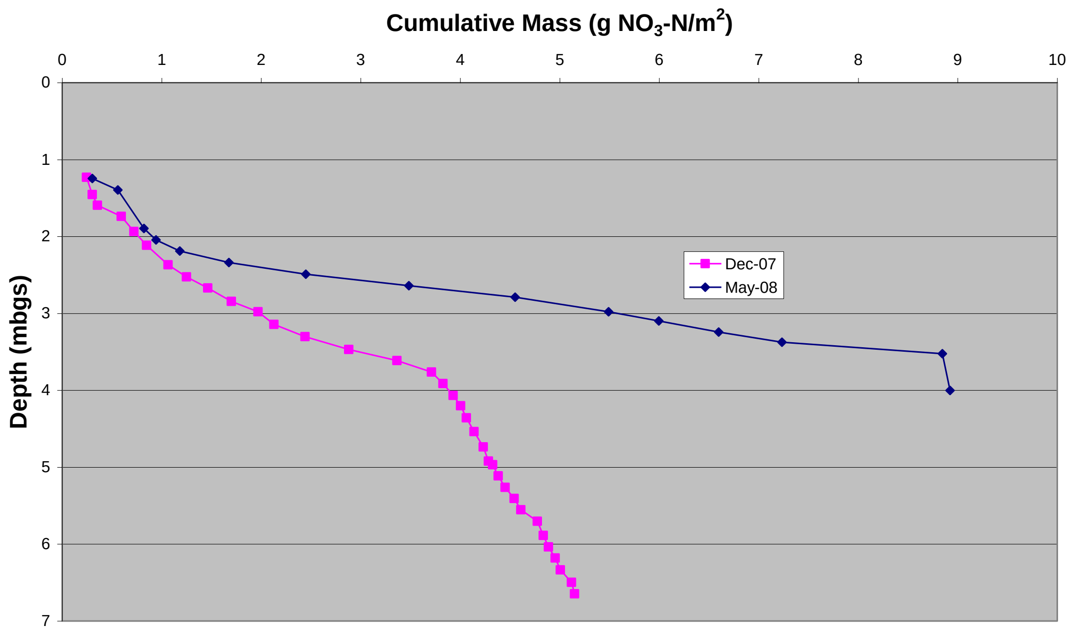


Figure J.4. Cumulative nitrate mass versus depth at Station 11.

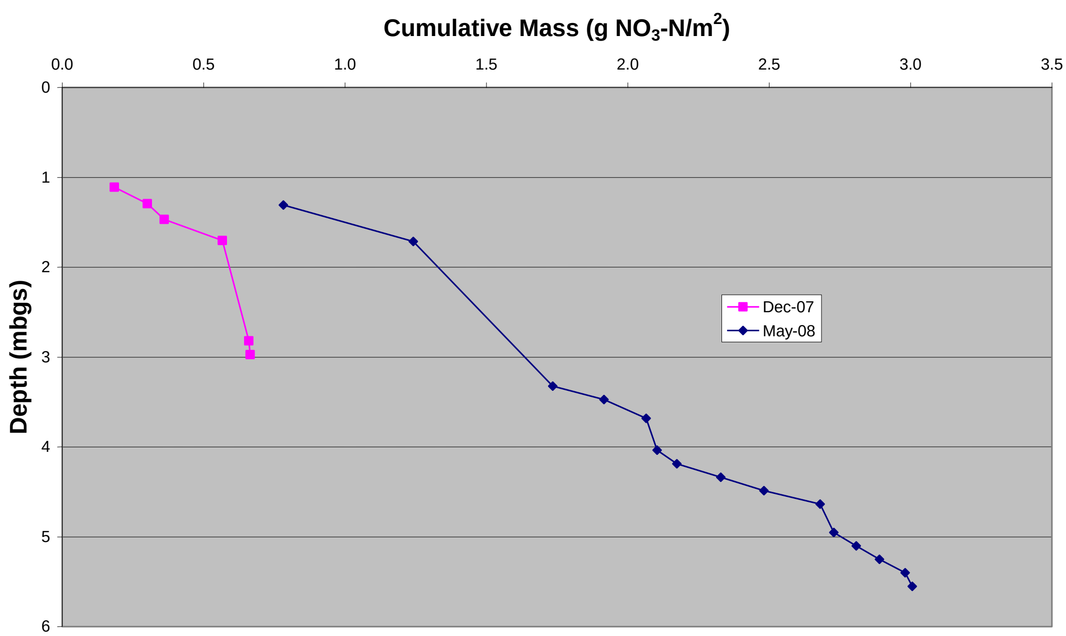


Figure J.5. Cumulative nitrate mass versus depth at Station 12.

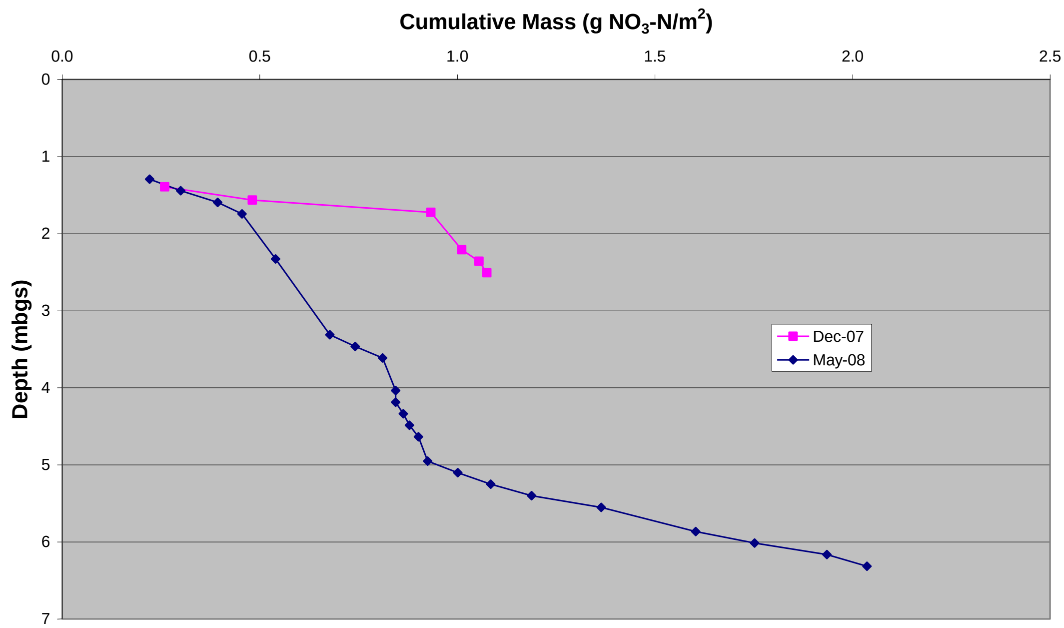


Figure J.6. Cumulative nitrate mass versus depth at Station 13.

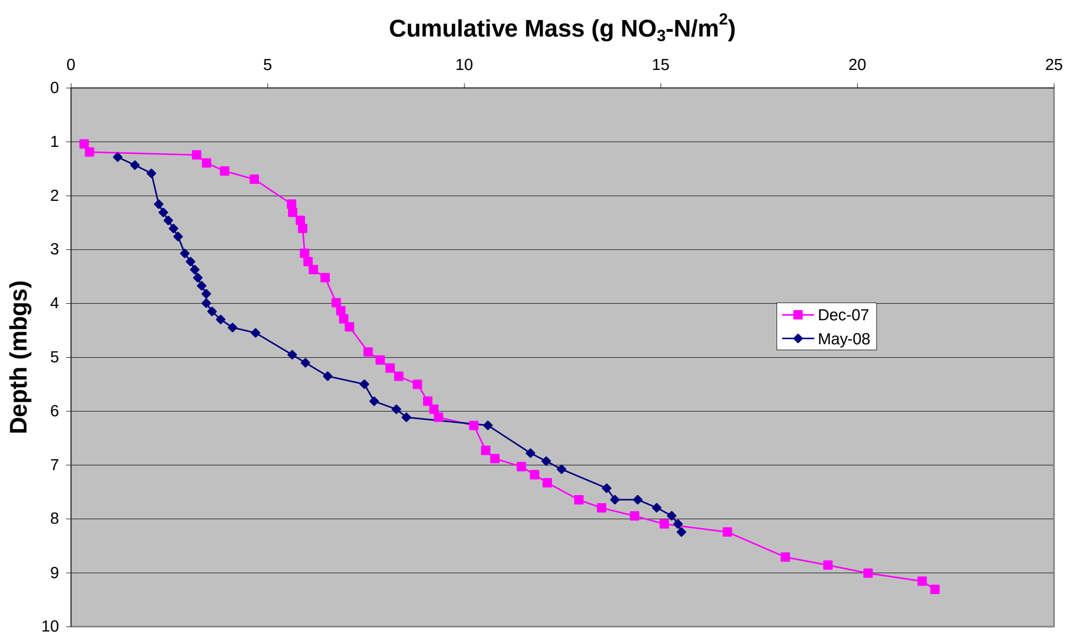


Figure J.7. Cumulative nitrate mass versus depth at Station 14.

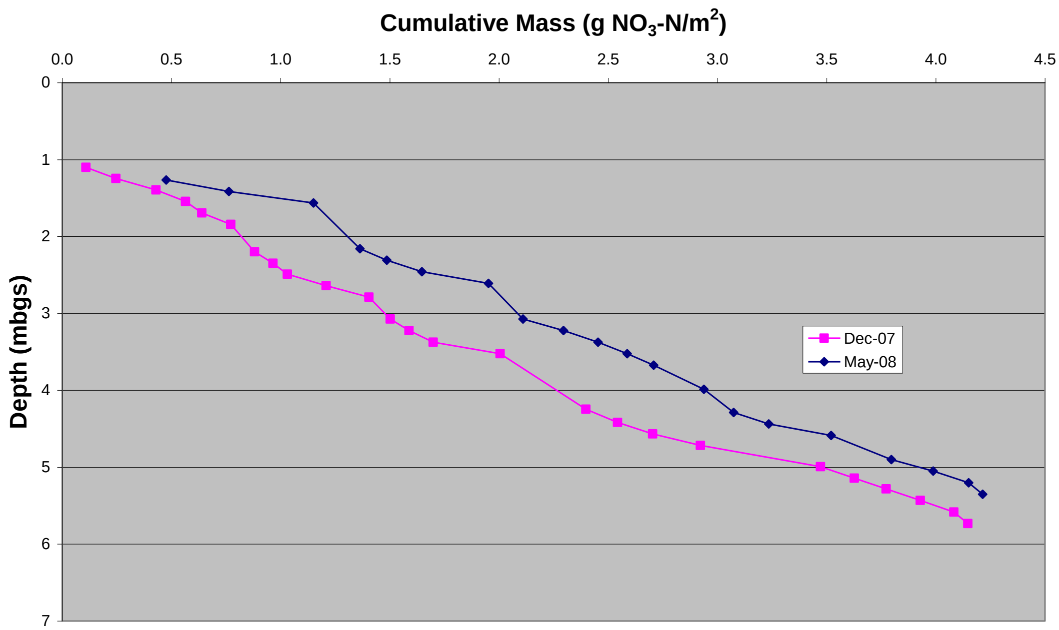


Figure J.8. Cumulative nitrate mass versus depth at Station 15.

Appendix K: Upscaled Porewater Nitrate Concentration Maps

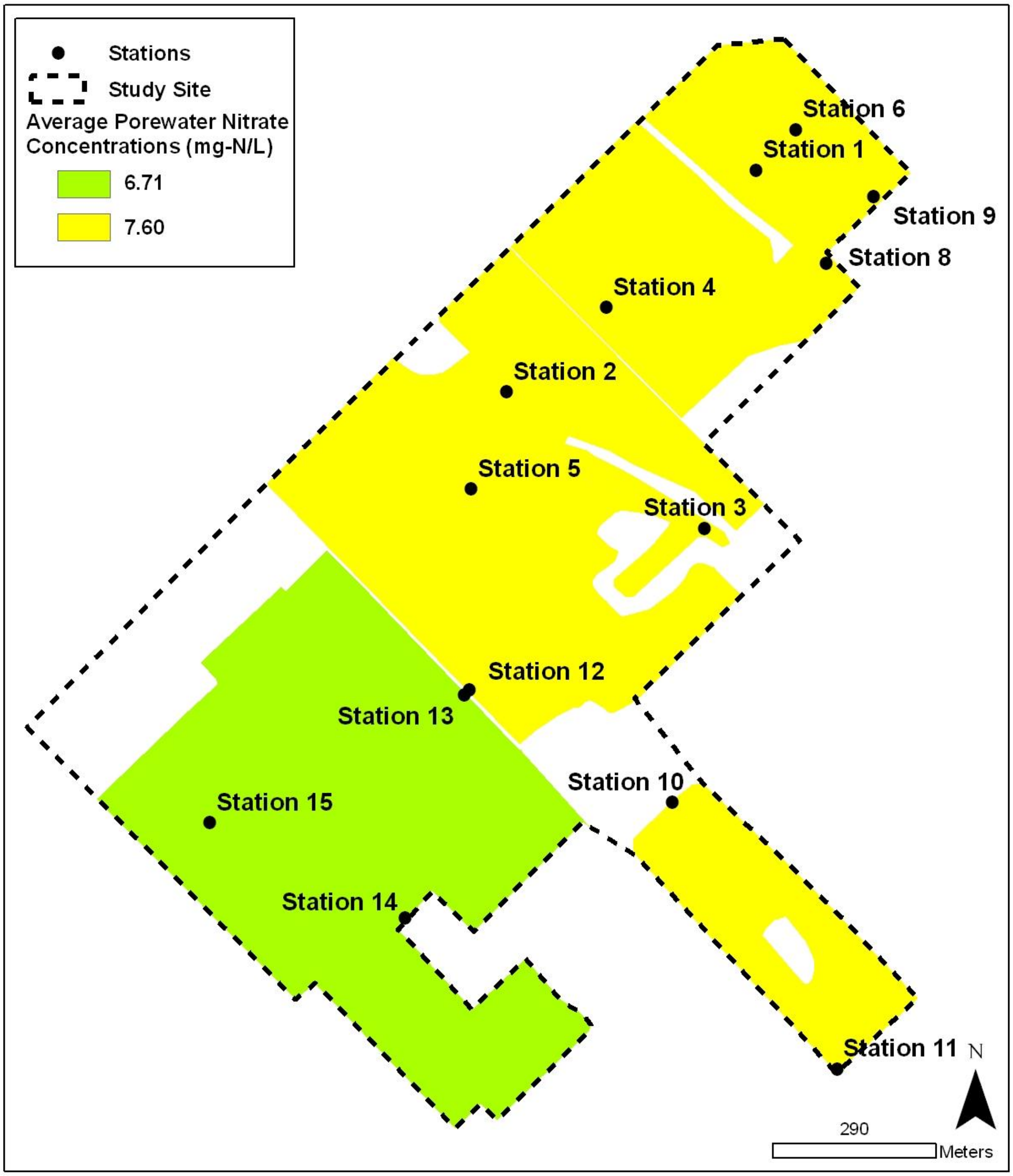


Figure K.13. Upscaled average porewater nitrate concentrations (May 2008) used to determine nitrate loading using method 1: average porewater nitrate concentrations.

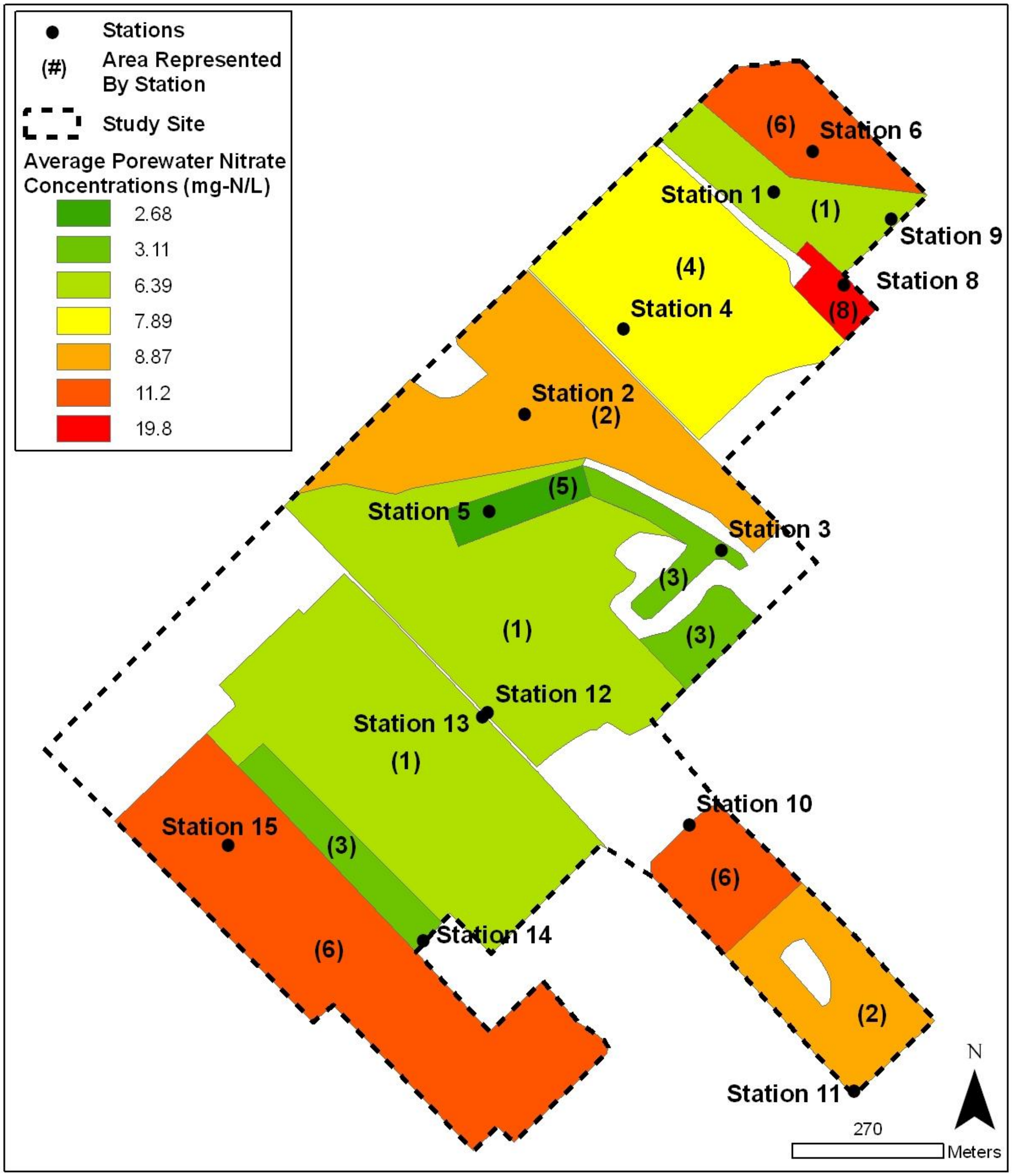


Figure K.14. Upscaled average porewater nitrate concentrations used to determine nitrate loading using method 2: geology, topography, recharge, field observations criteria.

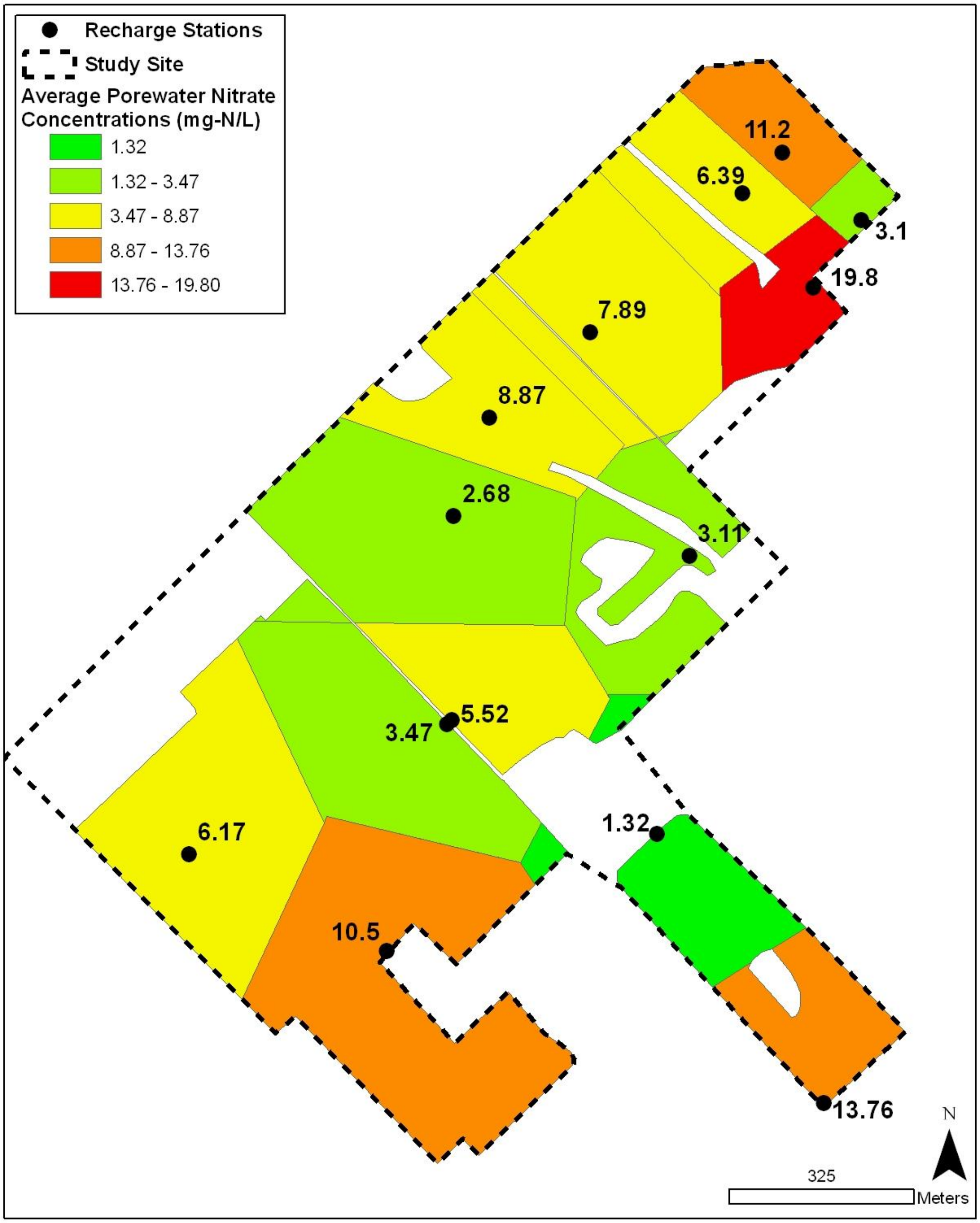


Figure K.15. Upscaled average porewater nitrate concentrations used to determine nitrate loading using method 3: Thiessen polygons.

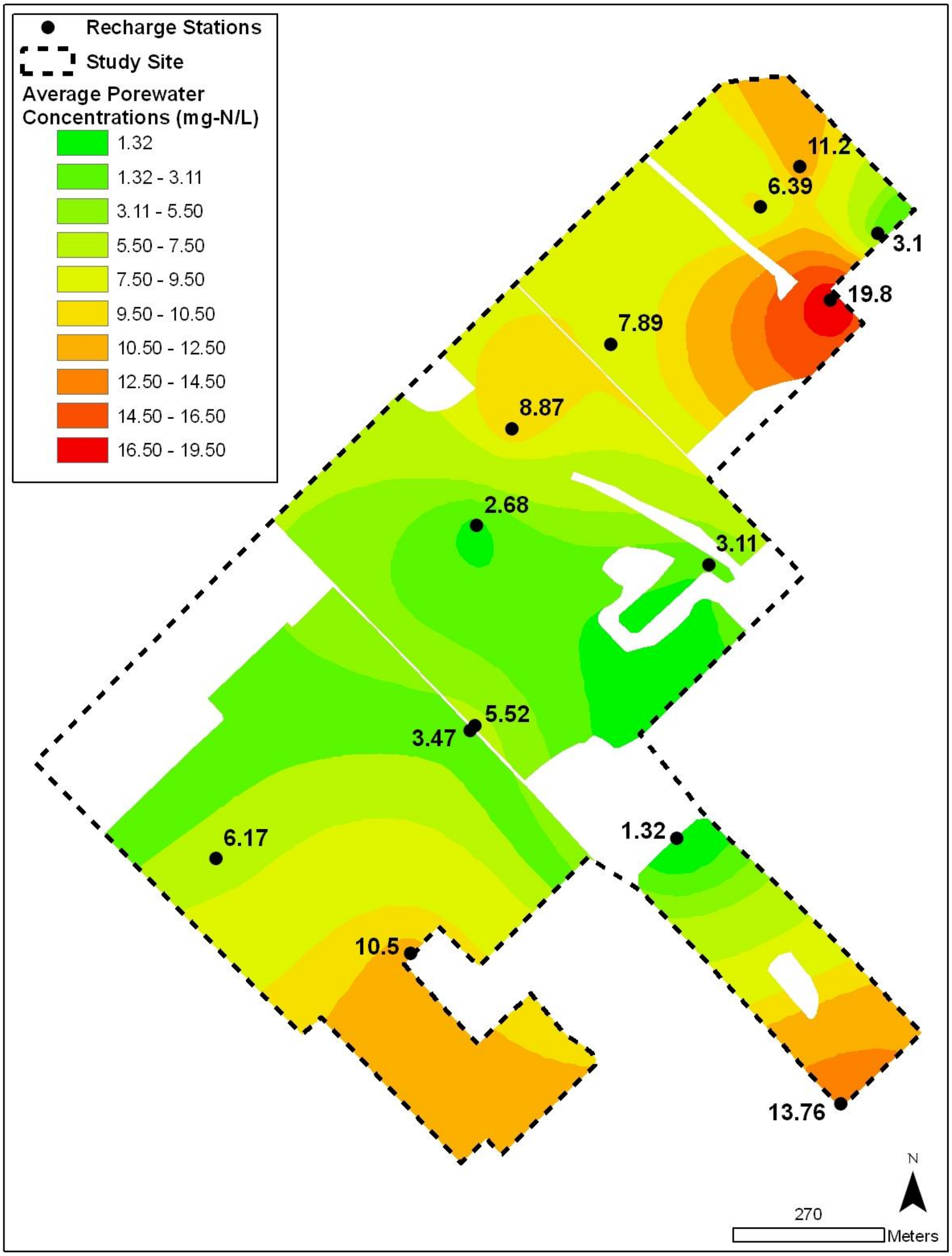


Figure K.16. Upscaled average porewater nitrate concentrations used to determine nitrate loading using method 3: Thiessen polygons.

Appendix L: Details of Nitrate Mass Loading Calculation

Table L.1: Upscaled nitrate mass loading data

	Area "Type"	Area (m^2)	Mass Flux ($g\ NO_3\text{-}N/m^2/yr$)	Nitrate Mass Loading (t/yr)
Method 1	Parcel A	442079	3.93	**1.74**
	Parcel B	742639	3.44	**2.55**
Method 2	Parcel A			
	6	200238	4.40	0.88
	1	212136	3.24	0.69
	3	29704	1.24	0.04
	Parcel B			**1.61**
	1	191821	3.24	0.62
	2	60460	3.70	0.22
	6	38162	4.40	0.17
	2	145404	3.70	0.54
	8	11574	10.34	0.12
	4	145565	3.71	0.54
	6	46579	4.40	0.20
	1	50626	3.24	0.16
	5	15823	1.40	0.02
	3	19020	1.24	0.02
	3	17604	1.24	0.02
Method 3	Parcel A			**2.65**
		116428	2.09	0.14
		135813	3.03	0.41
		179154	6.95	1.25
		5949	1.40	0.01
		4492	0.67	0.00
Method 3	Parcel B			**1.81**
		67866	2.07	0.14
		19708	3.71	0.07
		39983	4.40	0.18
		22217	1.24	0.03
		364	1.24	0.00
		47186	5.27	0.25
		146739	1.40	0.21
		51314	0.67	0.03
		4694	0.67	0.00
		78266	3.70	0.29

		50060	1.24	0.06
		102305	3.71	0.38
		21772	3.24	0.07
		39174	3.24	0.13
		11210	1.48	0.02
		39214	10.34	0.41
Method 4	Parcel A			**2.26**
		82273	3.50	0.29
		56089	4.50	0.25
		45042	5.50	0.25
		155156	2.50	0.39
		4290	1.50	0.01
		23957	5.50	0.13
		75312	6.50	0.49
Method 4	Parcel B			**1.80**
		59367	3.50	0.21
		80371	3.50	0.28
		23431	3.50	0.08
		41399	4.50	0.19
		28652	4.50	0.13
		4978	5.50	0.03
		20113	5.50	0.11
		25131	4.50	0.11
		39012	3.50	0.14
		94777	2.50	0.24
		24443	2.50	0.06
		17118	1.50	0.03
		12990	0.50	0.01
		2954	0.50	0.00
		10400	1.50	0.02
		850	1.50	0.00
		3480	2.50	0.01
		186843	1.50	0.28
		3157	6.50	0.02
		12302	6.50	0.08
		10967	7.50	0.08
		9429	8.50	0.08
		4573	9.50	0.04
		121	10.50	0.00
		1983	5.50	0.01
		12262	3.50	0.04
		7163	2.50	0.02
		4371	1.50	0.01
				2.30